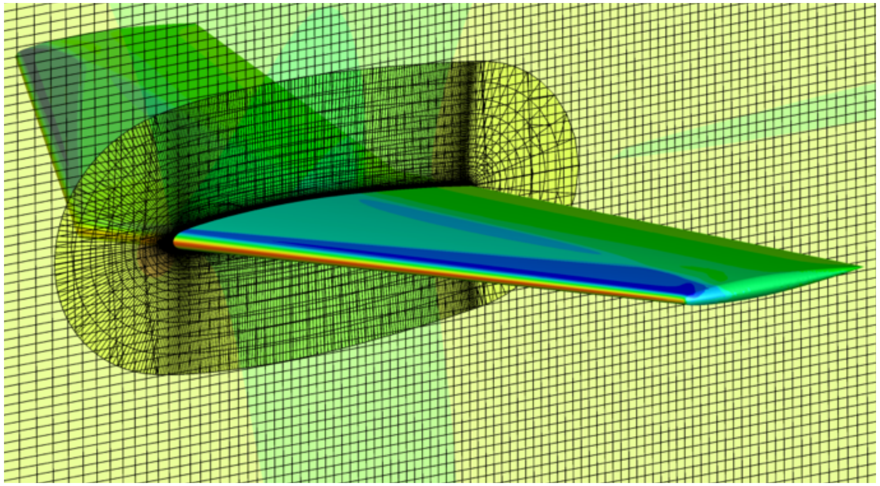
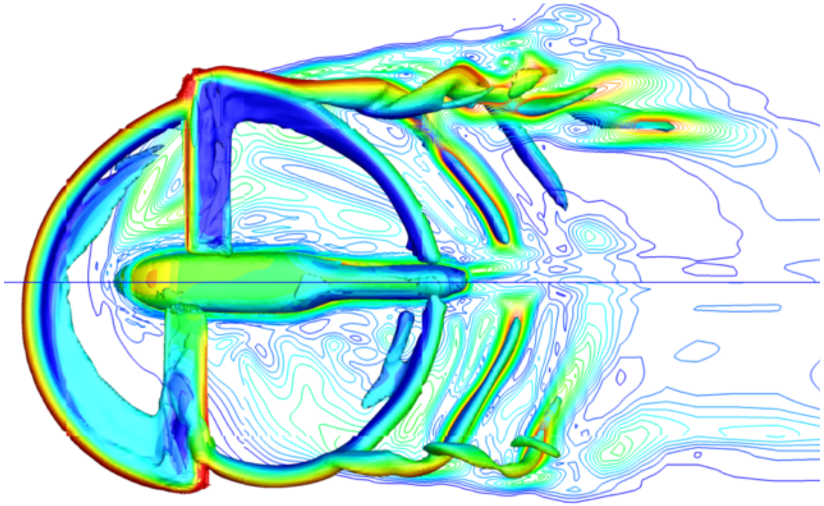
A Structured-Unstructured Overset Framework for Aerodynamic Flows using CPU/GPU Computing





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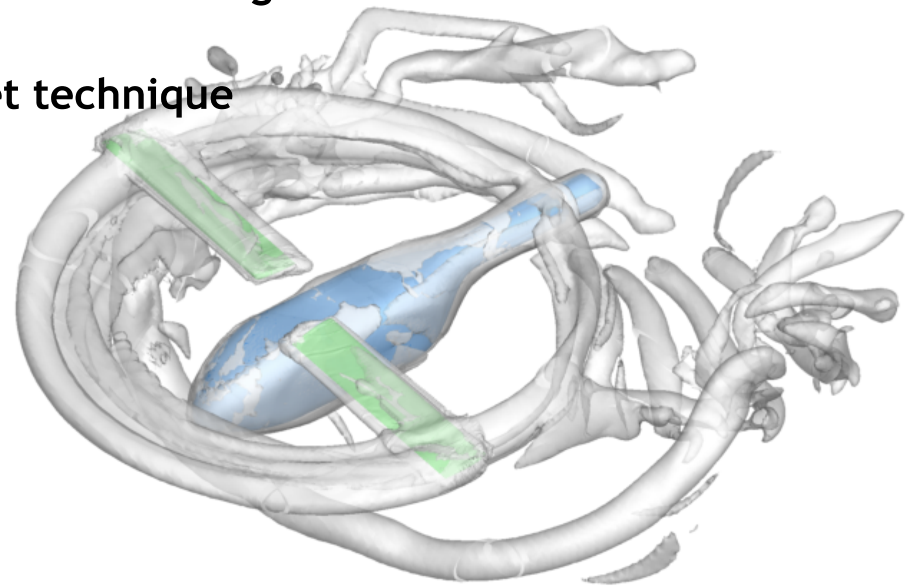
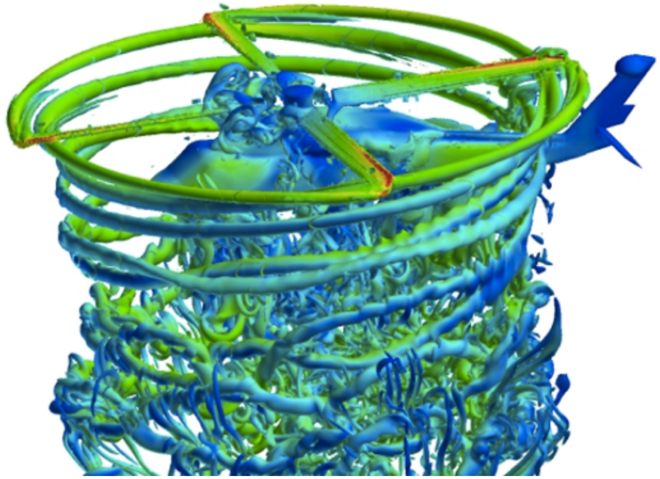
13th Symposium on Overset Composite Grids and Solution Technology, Mukilteo, WA

Outline

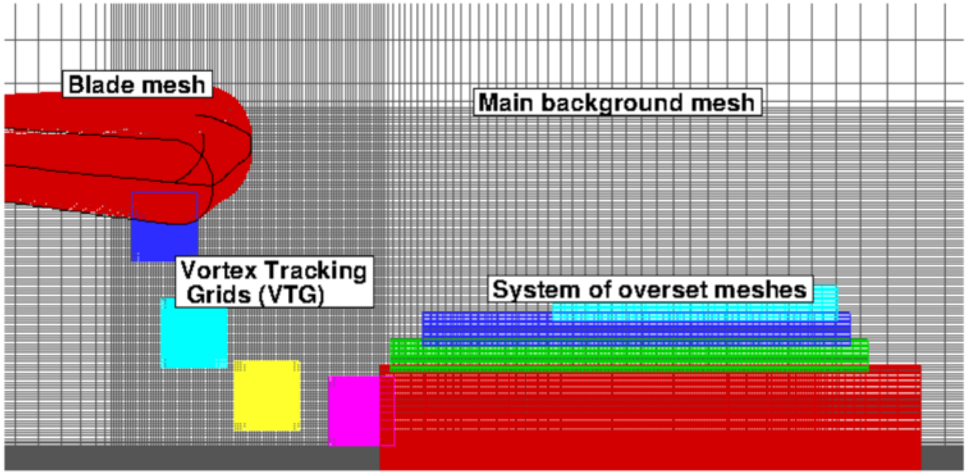
- Motivation and Introduction
- Methodology
  - HAMSTR: Line methods on unstructured grids
  - GARFIELD: GPU Accelerated solver on structured grids
  - TIOGA: Topology independent overset technique
  - Flow solvers
- Results
- Conclusions



Introduction



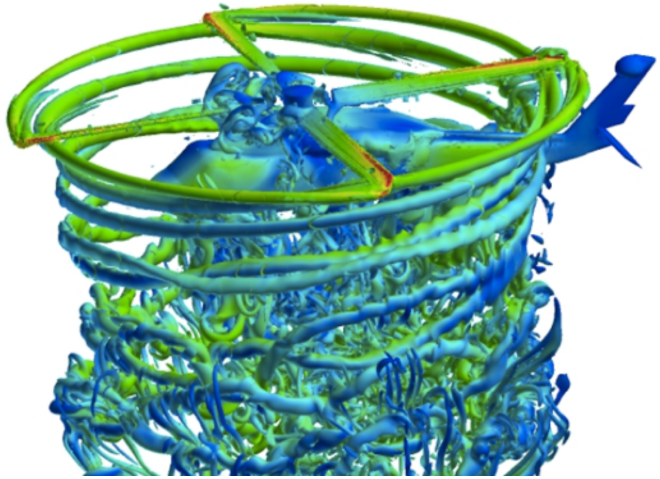
Flow in hover (Source: Helios)



Overset Cartesian Mesh (highlighting VTGs)

- Unsteady flow physics around complex configurations
- Multiple mesh system using overset technique
  - Unstructured grids for near-body region
  - Structured Cartesian grids for off-body region
- Heterogenous computing
  - Flow feature resolution can result in increases mesh sizes (e.g., AMR, VTG)
  - Use of CPUs and GPUs to reduce computational time

Introduction



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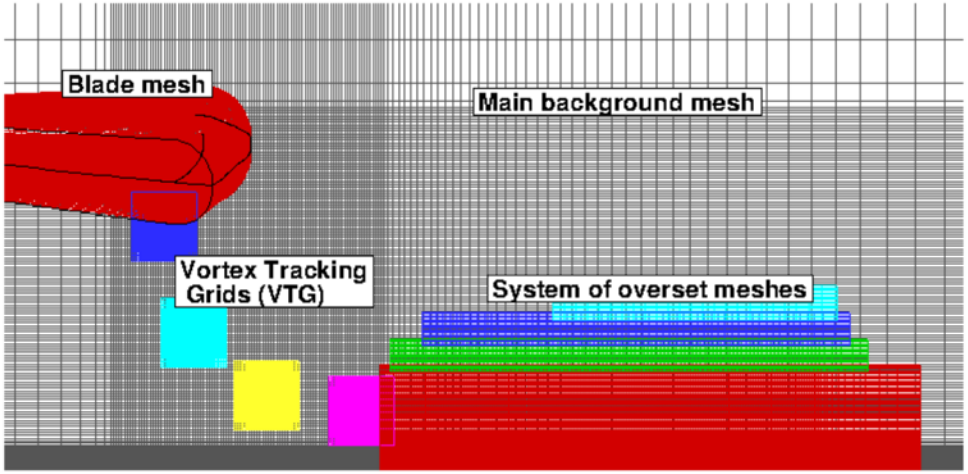


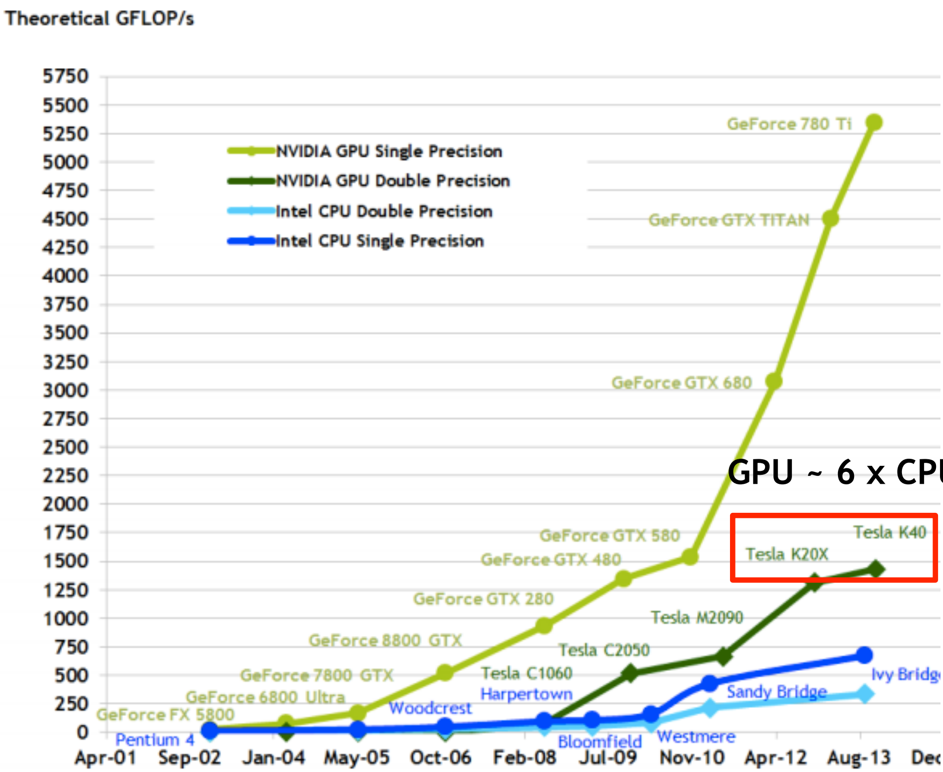
Overset Cartesian Mesh

- Structured grids solution methods
  - Stencil based discretization resulting in line-based implicit operator and solution schemes
  - "High-order type" numerical schemes are mature
  - Difficult to create for arbitrary geometries
- Unstructured meshes provide versatility for complex geometries
  - High-order difficult and expensive within a finite volume framework
  - Generally slower than their structured counterparts

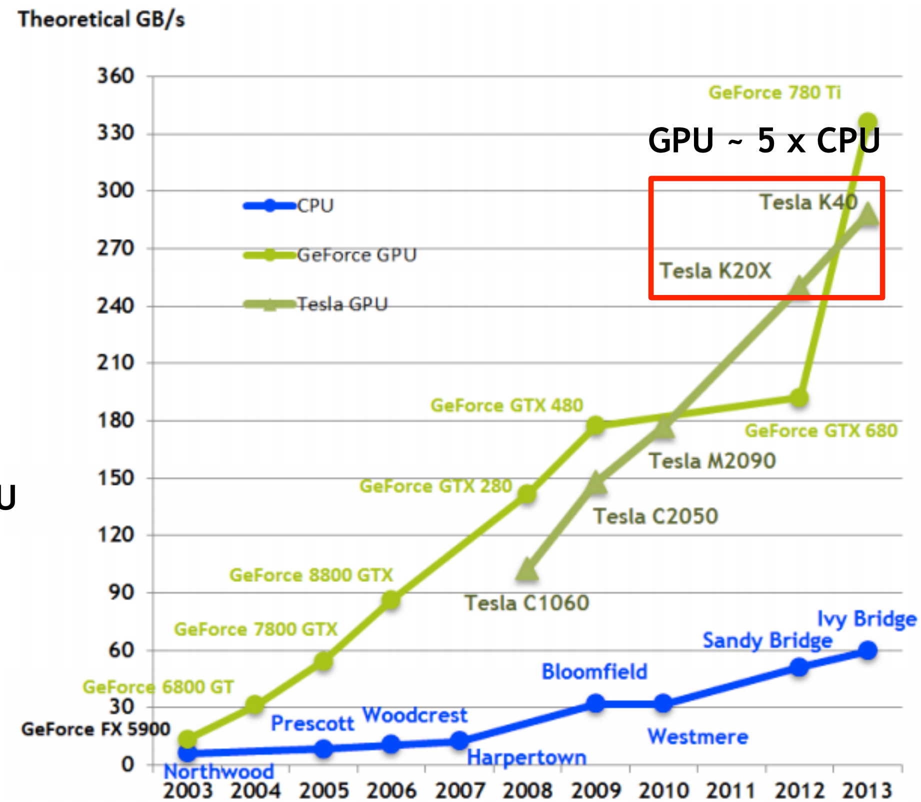
Previous Work

- Finding structures in unstructured grids
  - Hassan et al. (1989) and Martins and Lohner (1993): Abandoned because finding lines in pure unstructured grids was difficult and not robust (NP problem)
  - Mavriplis (1997): Line-implicit inversion in wall-normal direction
  - Meakin (2007), Wissink (2009), Katz (2011), Lakshminarayan (2016): Strand grids
- Paths in pure unstructured grids
  - Sitaraman and Roget (2014): Hamiltonian paths in 2D
  - Govindarajan et al. (2015) and Jung et al. (2016): Hamiltonian paths/ strand grids

GPU Computing



Operations per second



Memory bandwidth

GPUs can provide much higher computing performance than CPUs

Previous Work

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- Paths in pure unstructured grids
  - Sitaraman and Roget (2014): Hamiltonian paths in 2D
  - Govindarajan et al. (2015) and Jung et al. (2016): Hamiltonian paths/ strand grids
- GPU accelerated solvers
  - Soni, Chandar and Sitaraman (2012): Incompressible NS solver with overset
  - Khajeh-Saeed and Perot (2013): Direct Numerical Solution
  - Chan et al. (2016): GPU accelerated Discontinuous-Galerkin
  - Sebastian and Baeder (2013), Jude and Baeder (2016): GPU RANS

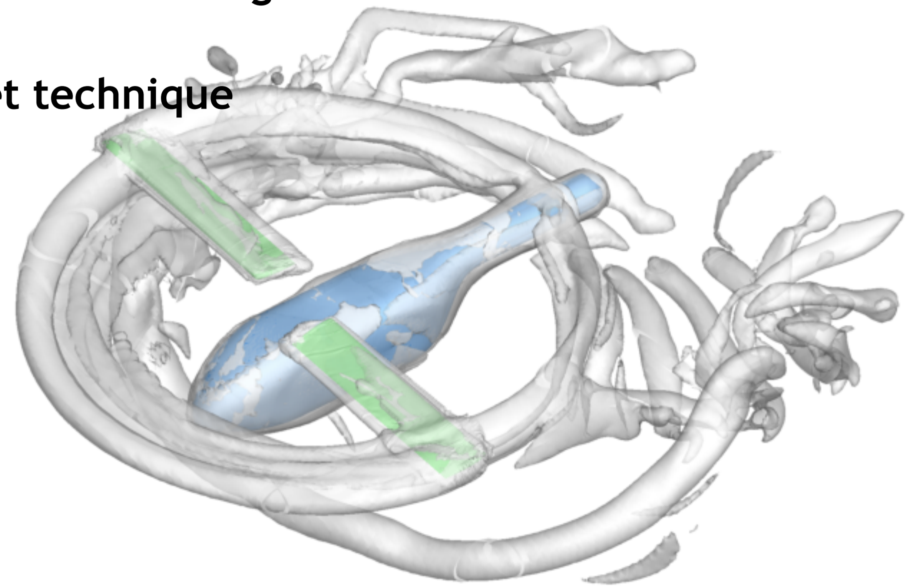
Objective

Formulate a line-based solver that is independent of mesh topology

Take advantage of the computing capabilities of GPUs

Validate for practical aerodynamics flows within an overset framework

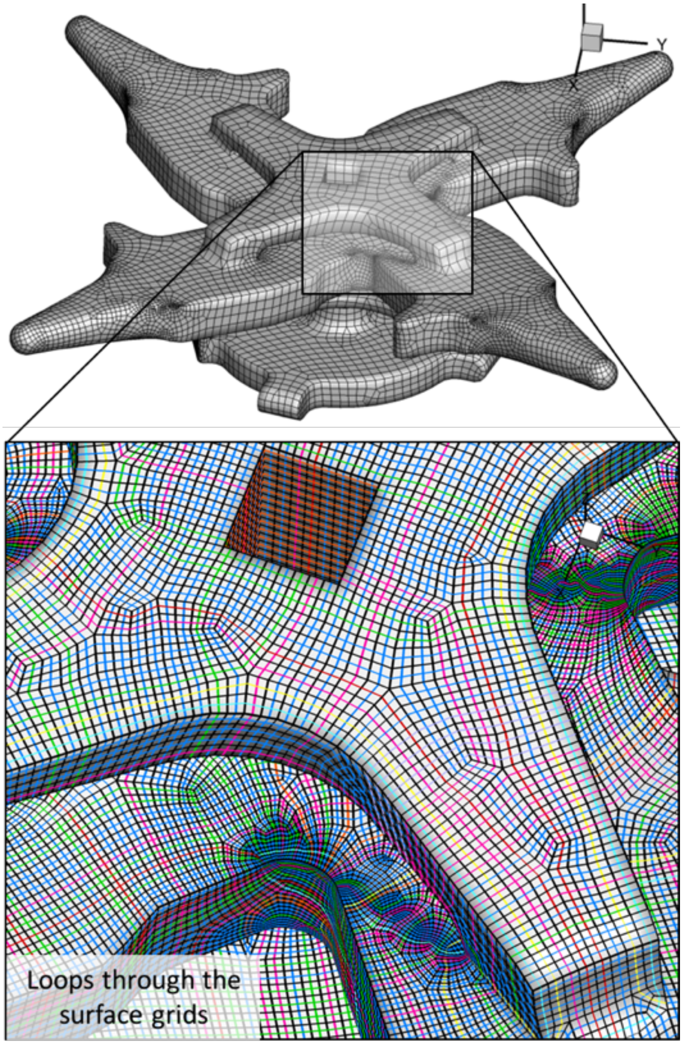
- Motivation and Introduction
- Methodology
  - HAMSTR: Line methods on unstructured grids
  - GARFIELD: GPU Accelerated solver on structured grids
  - TIOGA: Topology independent overset technique
  - Flow solvers
- Results
- Conclusions



HAMSTR Capabilities

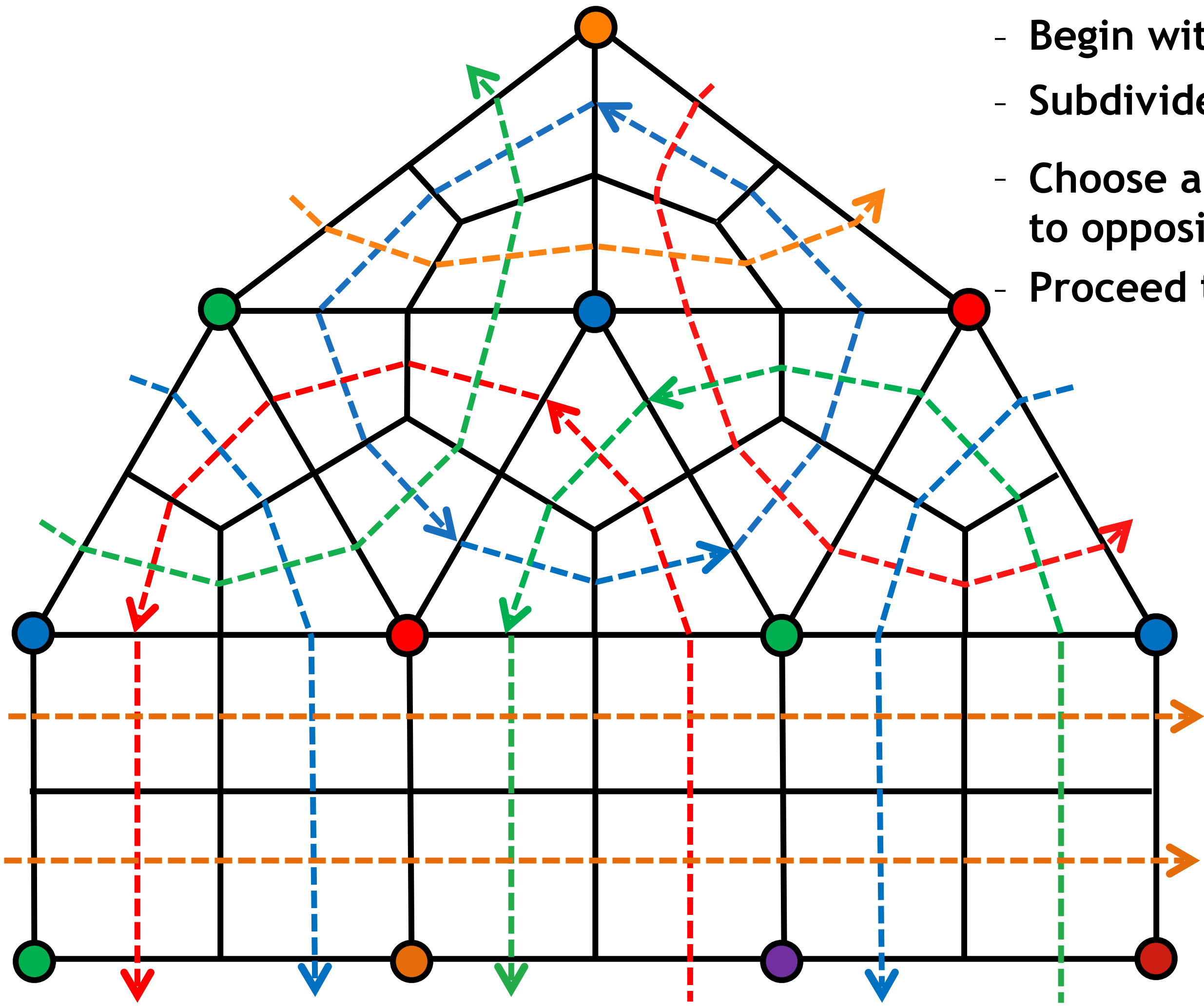
HAMSTR: Hamiltonian-Strand

- Line-based solver on unstructured grids
- Three-dimensional Navier—Stokes solver
- Viscous and turbulence models
- Overset framework
- Grids move relative to each other
- Parallelized using MPI
- Start from mixed-element surface mesh
- Integrated through Python



Developed under Air Vehicles element of the HPCMP CREATE program through PETTT grant (2014—2016)

Multi-Element Surface Mesh



- Begin with original unstructured mesh
- Subdivide triangles and quadrilaterals
- Choose any “available” face and link to opposite face of the cell
- Proceed till all faces are part of a loop

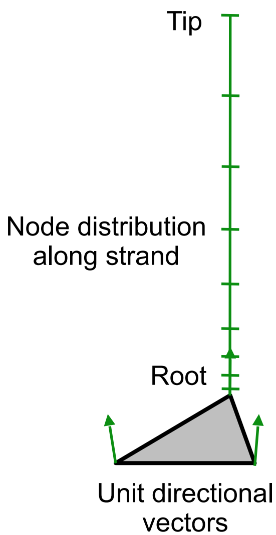
Every cell has two coordinate directions

Loops equivalent to traditional lines

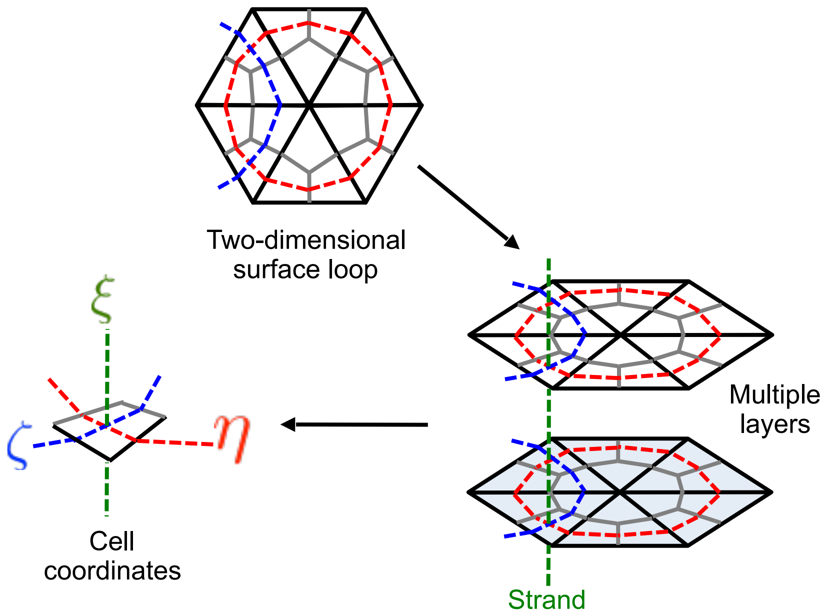
The coloured loops are Hamiltonian paths

Strand Grids

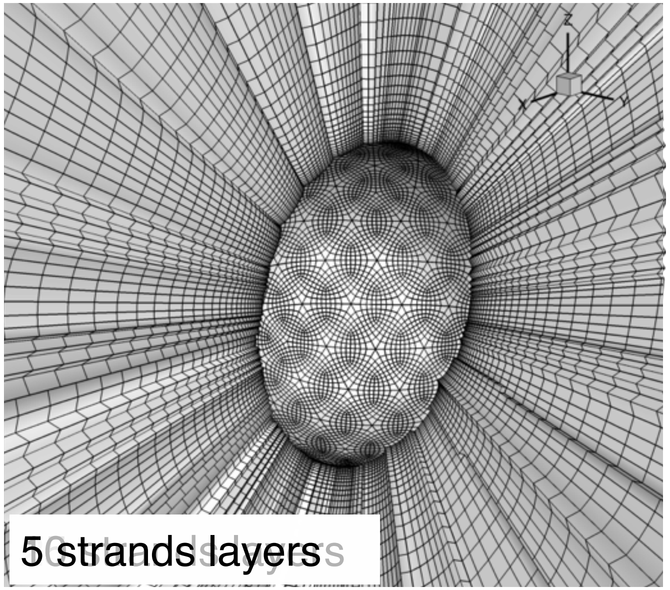
- Strands grids are employed to extend the formulation to three-dimensions
- Formed by extruding the surface mesh in wall normal direction
- Volume domain formed by “stacking” multiple Hamiltonian path layers
- Layers are connected with strands and forms the third spatial cell coordinate



Strand template



Strands and associated cell coordinates

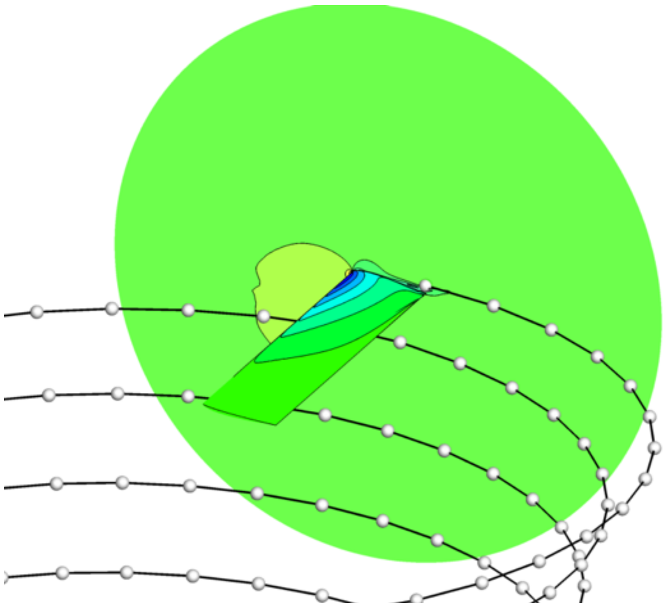


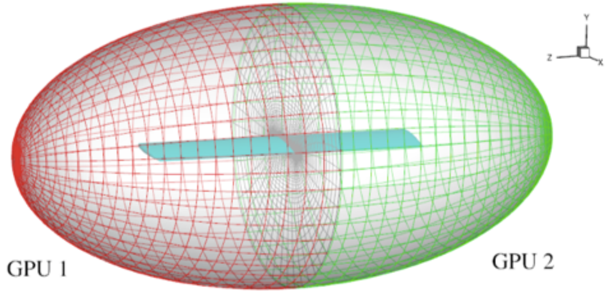
Growth on a sphere

GARFIELD Capabilities

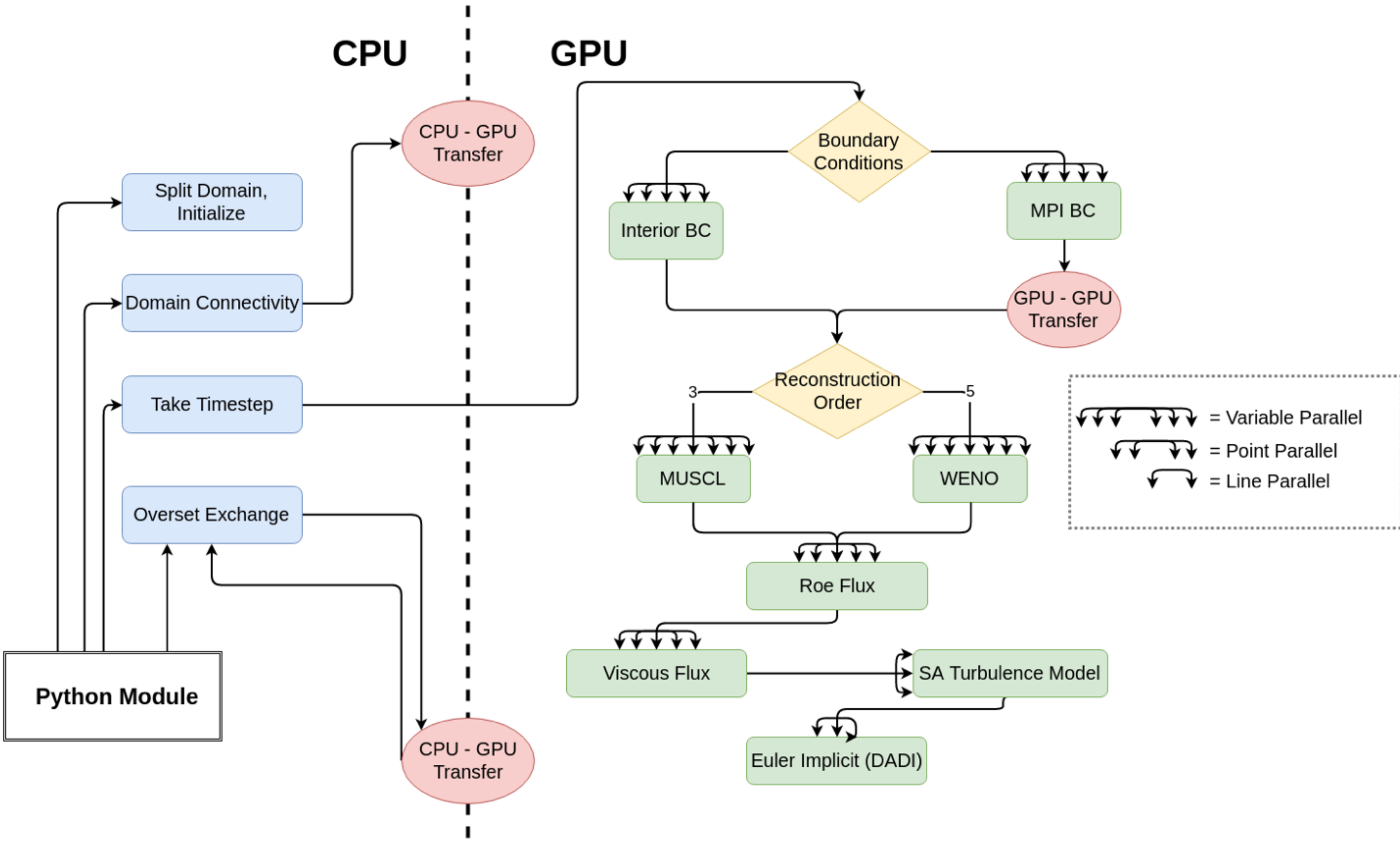
GARFIELD: GPU Accelerated Rotor Flow Field Solver

- GPU accelerated
- Line-Solver on curvilinear grids
- Three-dimensional Navier—Stokes solver
- Viscous and turbulence models
- Overset framework
- Parallelized across multiple GPUs using MPI
- Coupled to a free-vortex method
- Integrated through Python





RANS on GPUs

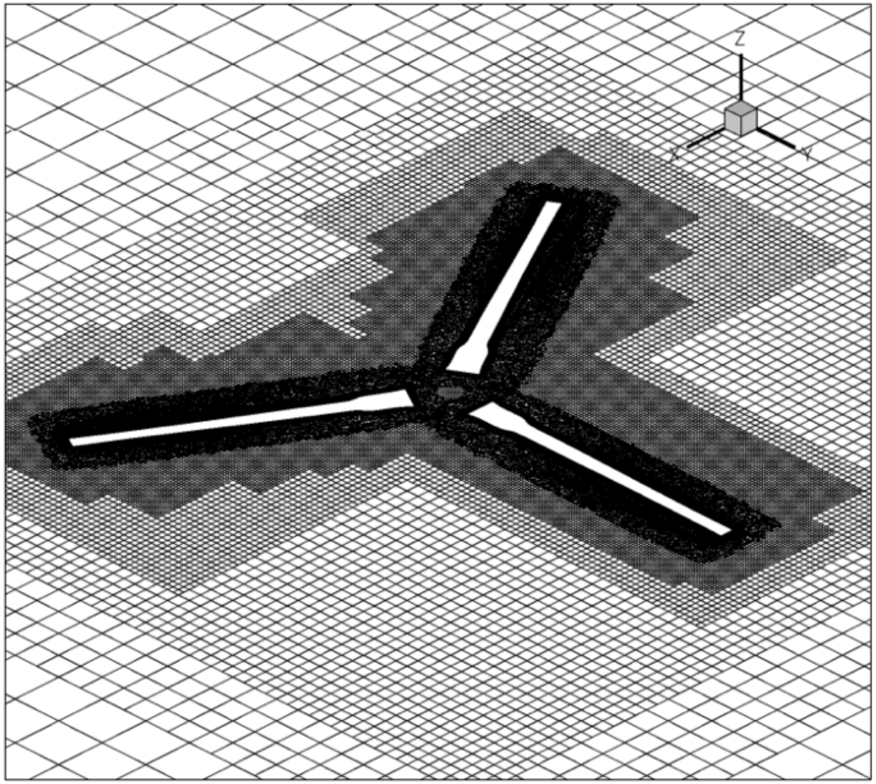


CPU
GPU
CPU - GPU Transfer
Split Domain, Initialize
Domain Connectivity
Take Timestep
Overset Exchange
Python Module
CPU - GPU Transfer
Boundary Conditions
Interior BC
MPI BC
GPU - GPU Transfer
Reconstruction Order
3
5
MUSCL
WENO
Roe Flux
Viscous Flux
SA Turbulence Model
Euler Implicit (DADI)
= Variable Parallel
= Point Parallel
= Line Parallel

Overset Connectivity

TIOGA*: Topology Independent Overset Grid Assembler

- **Developed by Jay Sitaraman**
- **Identify field, donor, receptor and holes**
- **Mixed element unstructured meshes**
- **Implicit hole cutting strategy**
- **Alternating Digital Tree for fast search**
- **Fully parallel across MPIs**
- **Integrated through Python**



**Brazell, M. J., Sitaraman, J., and Mavriplis, D. J., "An Overset Mesh Approach for 3D Mixed Element High-Order Discretization," Journal of Computational Physics, Vol. 322, pp. 33—51, 2016.*

Framework Integration

Communication through Python

HAMSTR

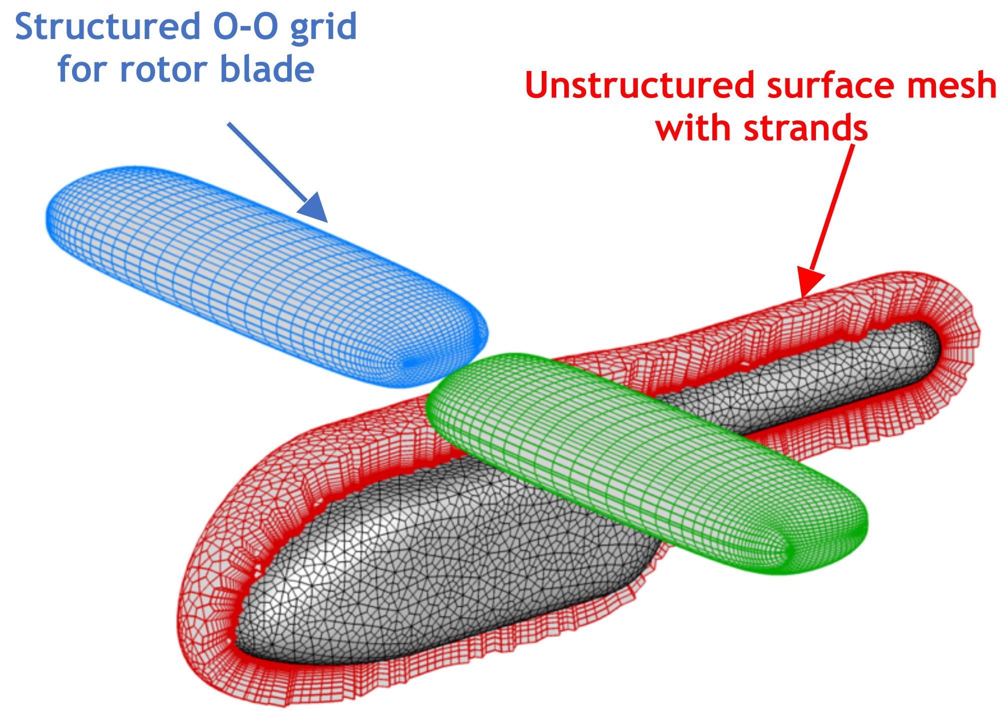
- Based on CPU Parallelized across multiple processors using MPI
- Solves along loops and strands in a manner similar to a structured grid
- Wrapped using Python (SWIG)

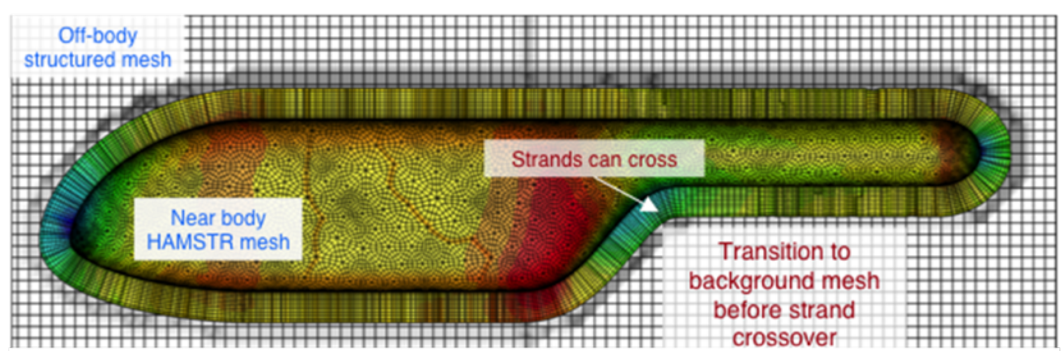
TIOGA

- Identifies the iblank arrays and interpolation weights
- Interface code written in C/C++
- Compiled into a library
- Accessible in Python

GARFIELD

- Based on Graphic processors units (GPU) using CUDA interface parallelized across multiple processors using MPI
- Structured grid based flow solver
- Wrapped using Python (Boost)



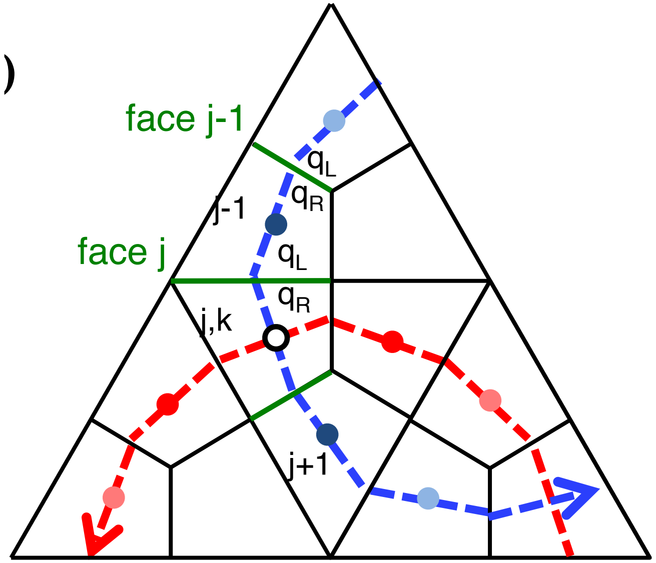


Governing Equations

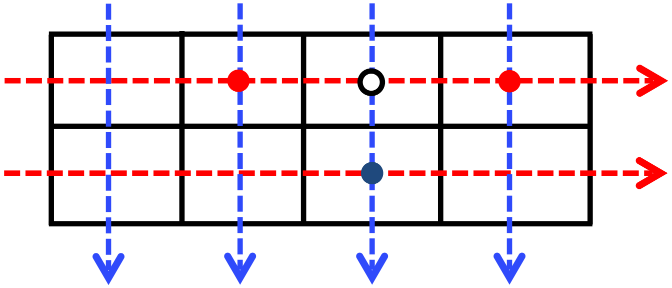
- 3D compressible Navier-Stokes formulation (Finite volume)

$$\frac{\partial \mathbf{q}}{\partial t} + \nabla \cdot [(\mathbf{F}_C - \mathbf{F}_V), (\mathbf{G}_C - \mathbf{G}_V), (\mathbf{H}_C - \mathbf{H}_V)] = 0$$

- Inviscid reconstruction can use standard line-methods (e.g., MUSCL, WENO, CRWENO)
- Implicit line-operators for factorization
  - HAMSTR: Diagonally Dominant Line Gauss Seidel (DDLGS)
  - GARFIELD: Diagonalized Alternating Direction Implicit (DADI)
- 2^{nd} order accurate in time using BDF
- Interface fluxes computed using Roe's scheme
- Viscous terms using 2^{nd} order central difference
- Spalart—Allmaras turbulence model for Eddy viscosity



HAMSTR: "loops" equivalent to traditional lines



GARFIELD: conventional lines

Solver formulation for both HAMSTR and GARFIELD very similar to structured grid solvers

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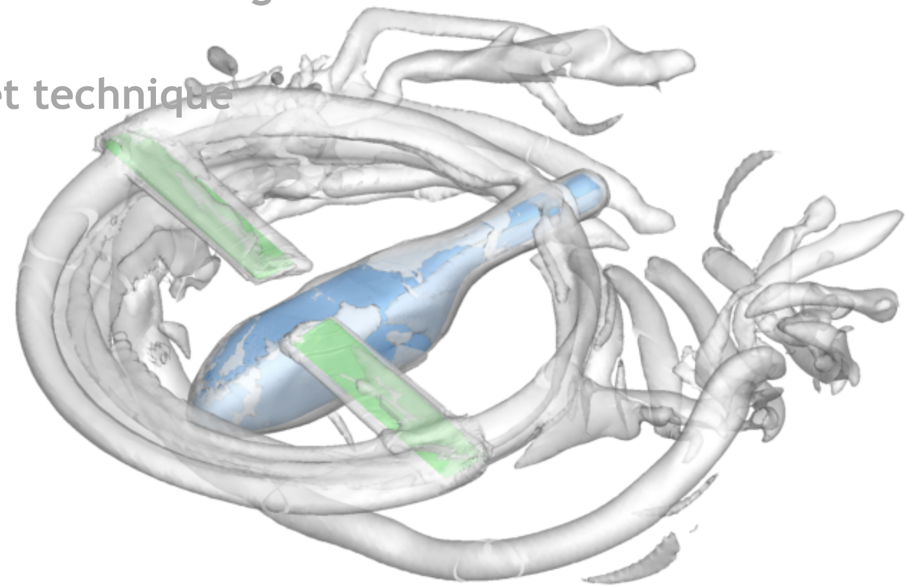
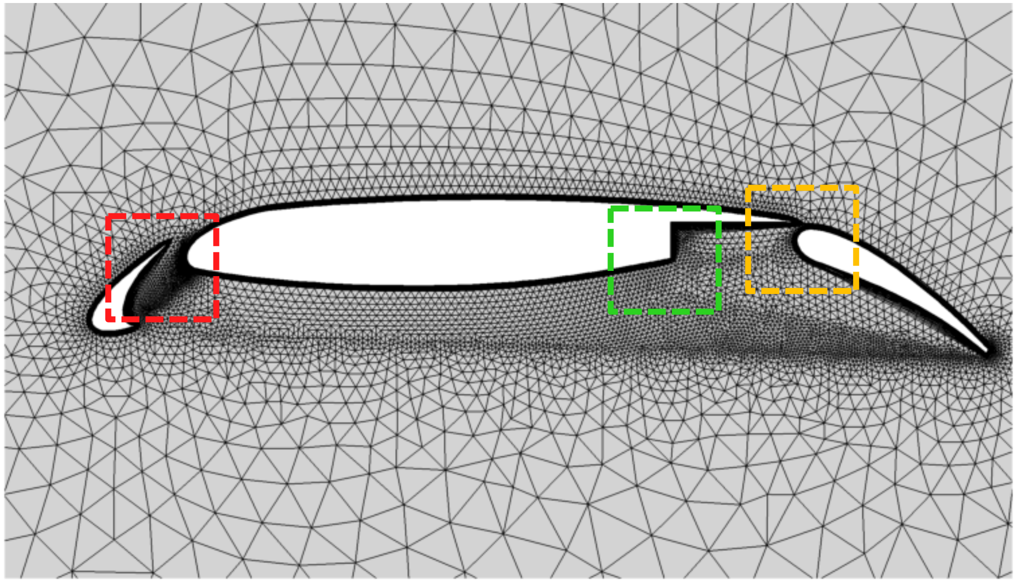
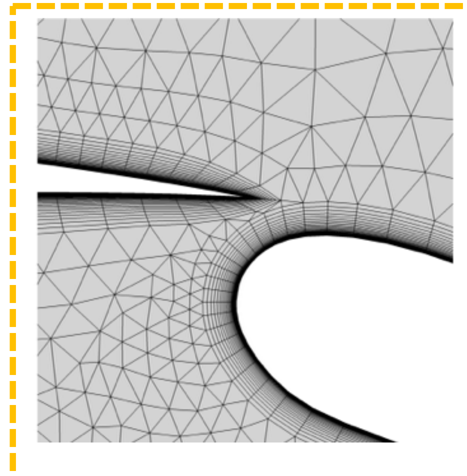


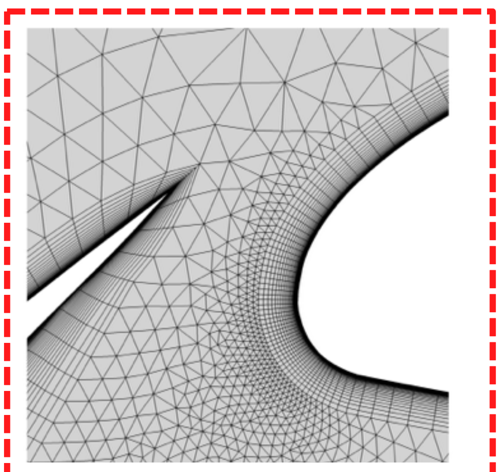
Three-Element Airfoil

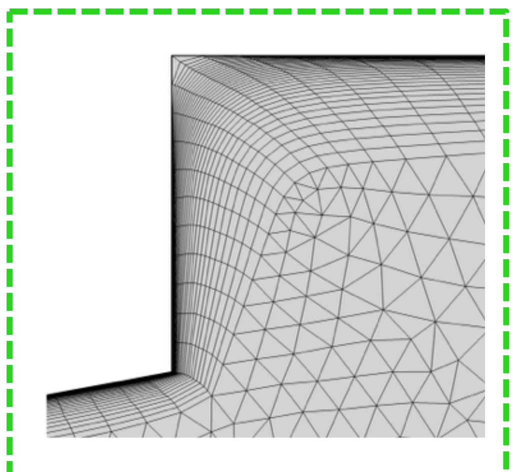
HAMSTR





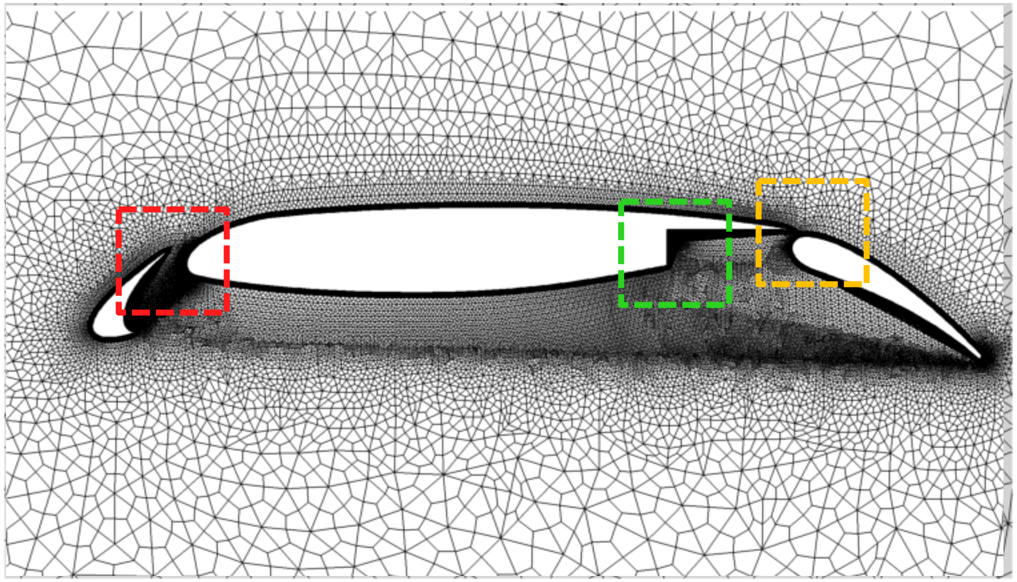
No. cells: 107,063
M = 0.2
AoA = 4°
Re = 9 million

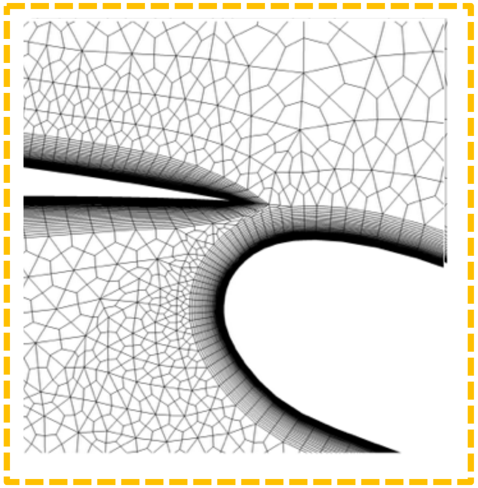




Three-Element Airfoil

HAMSTR





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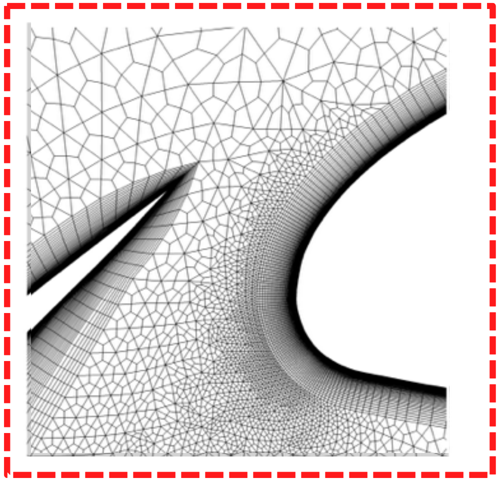
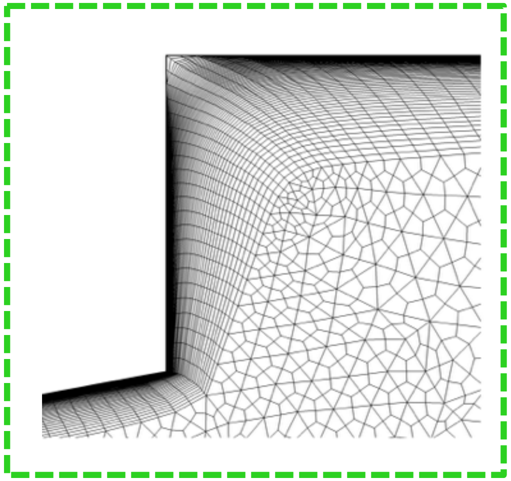
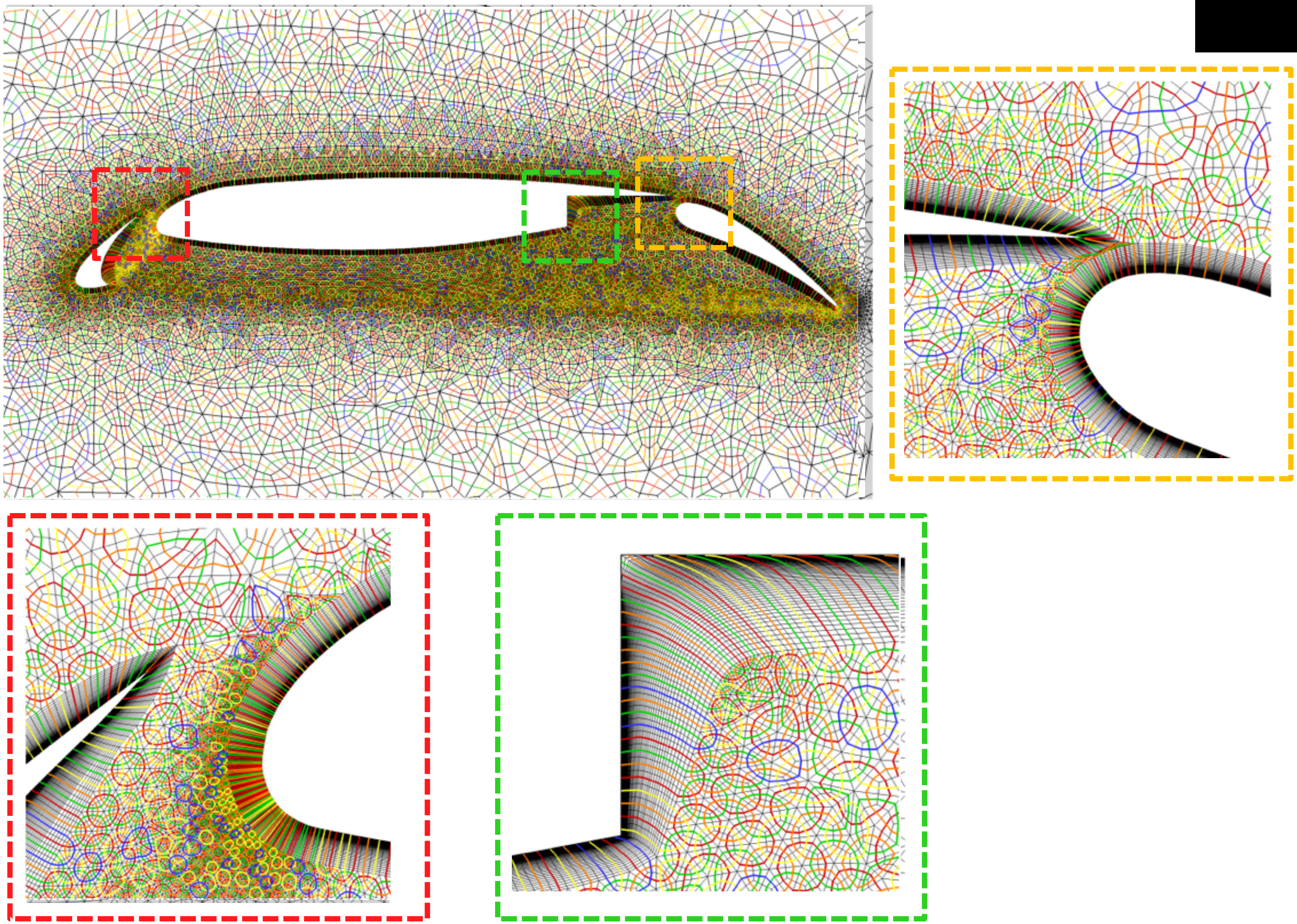




Three-Element Airfoil

HAMSTR



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Three-Element Airfoil

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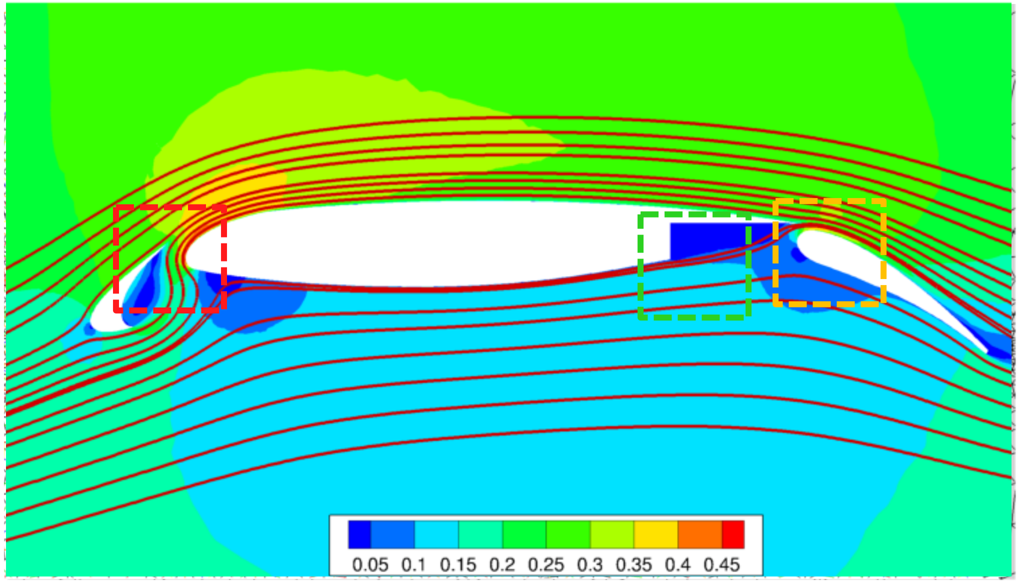

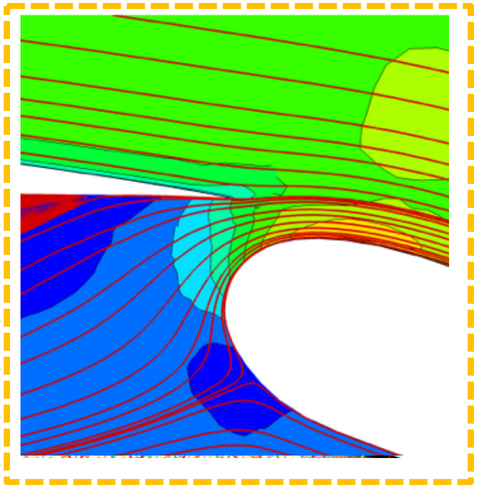

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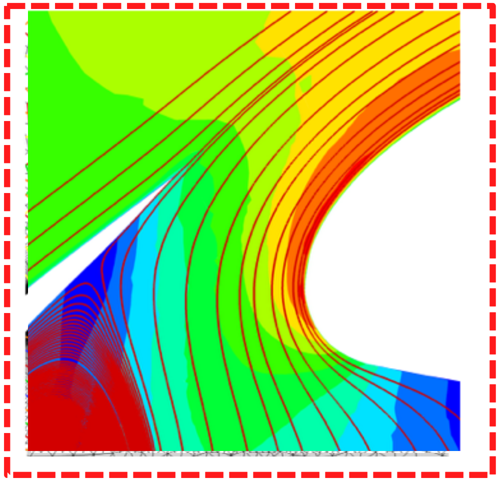
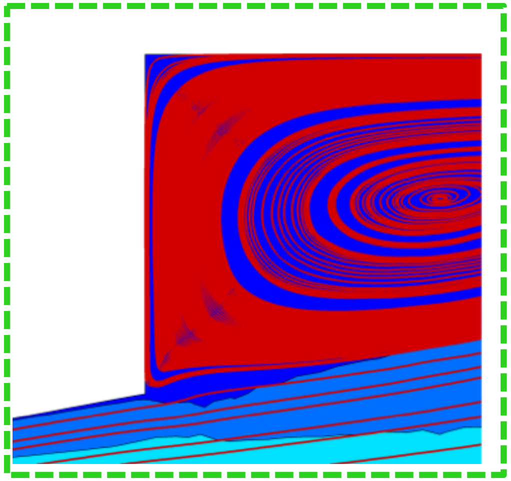
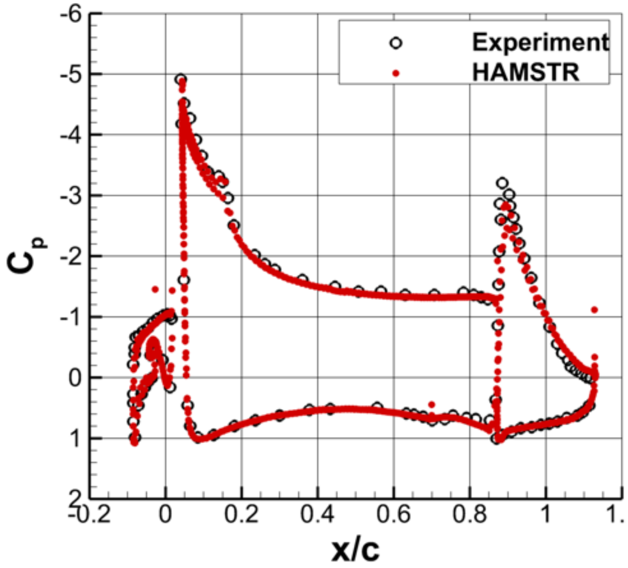


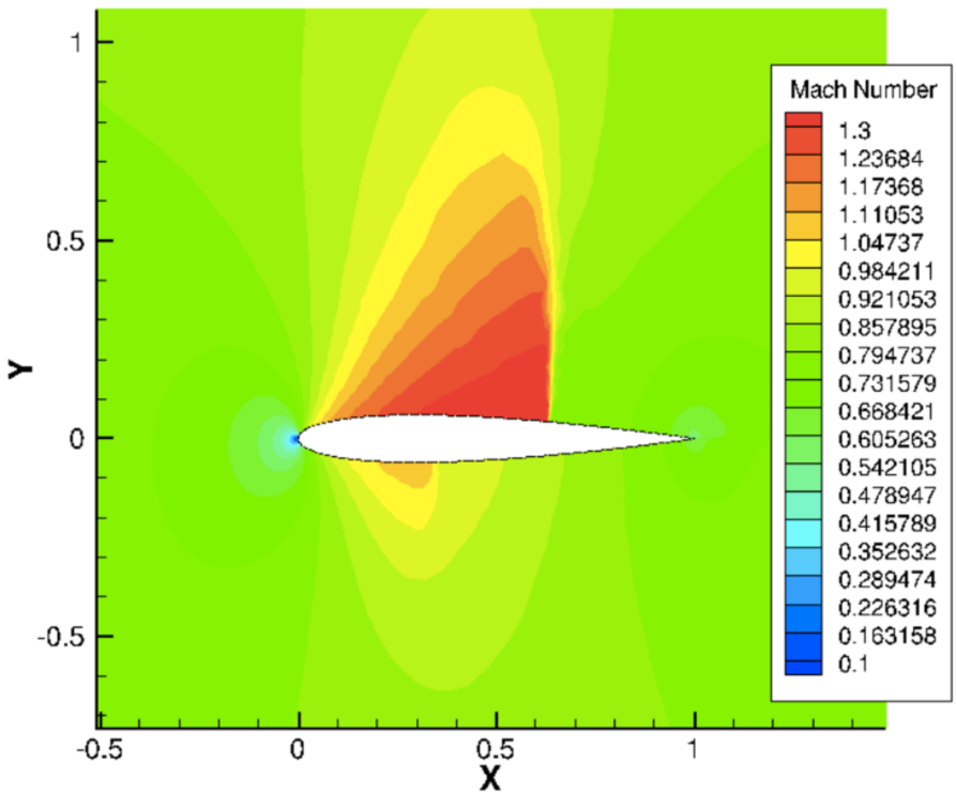


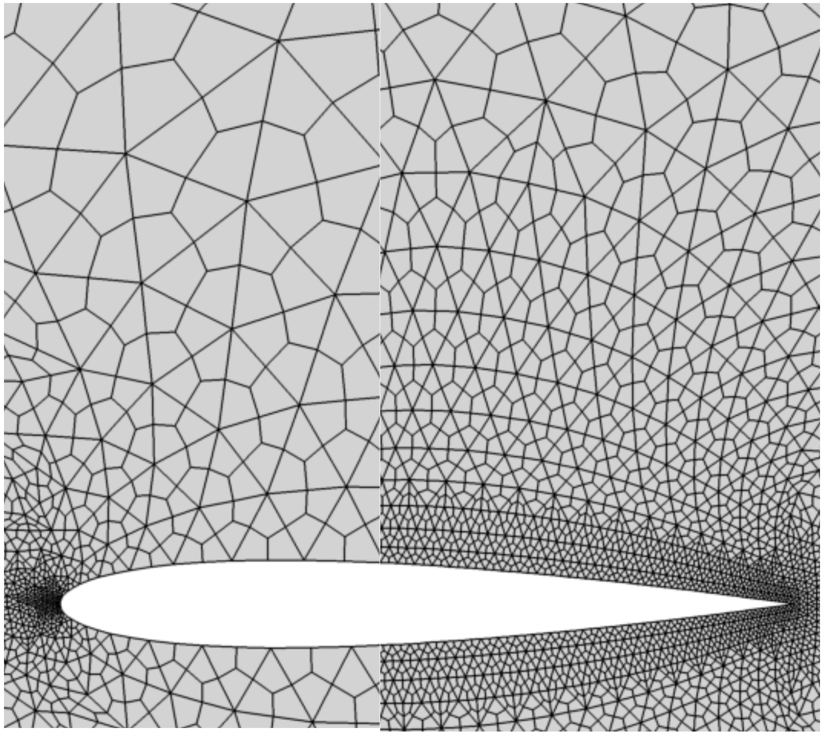


Streamlines on velocity contour

Order of Accuracy

HAMSTR

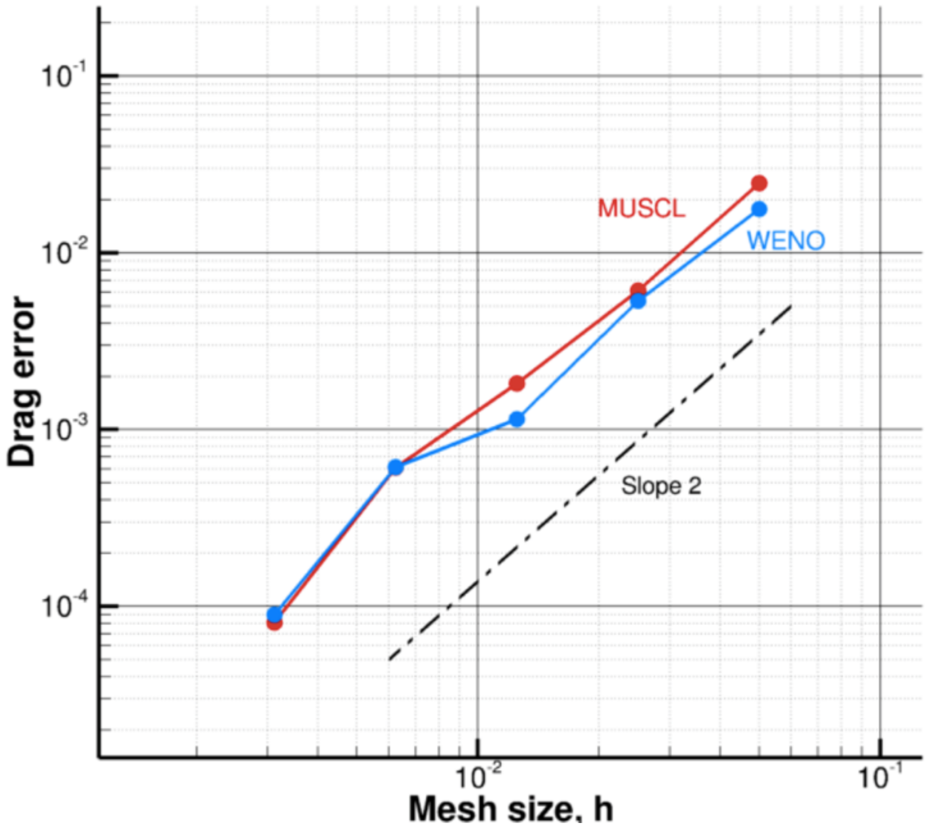


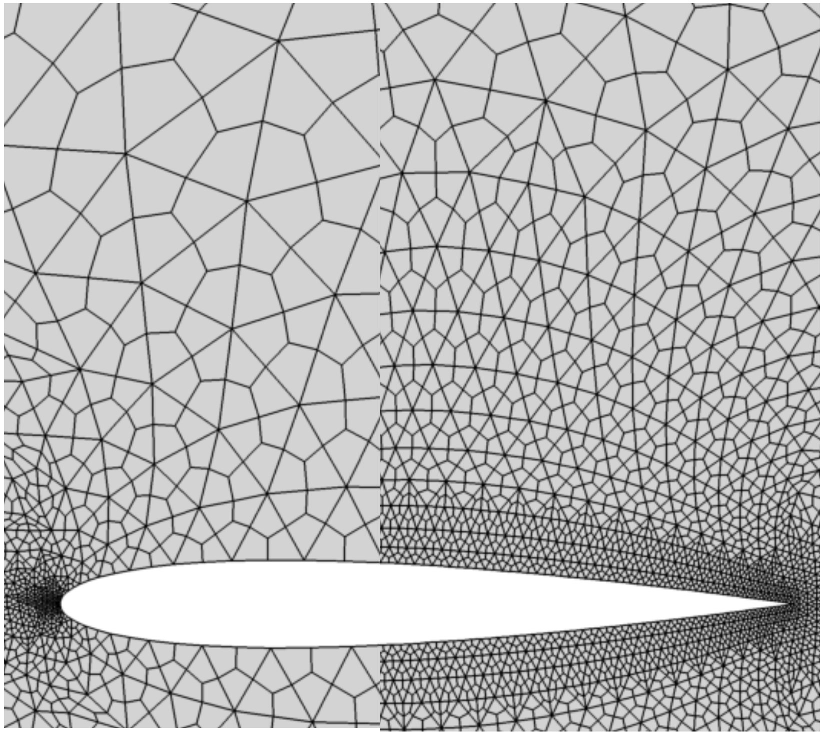


- M = 0.8, AoA 1.25, Inviscid transonic flow

Order of Accuracy

HAMSTR



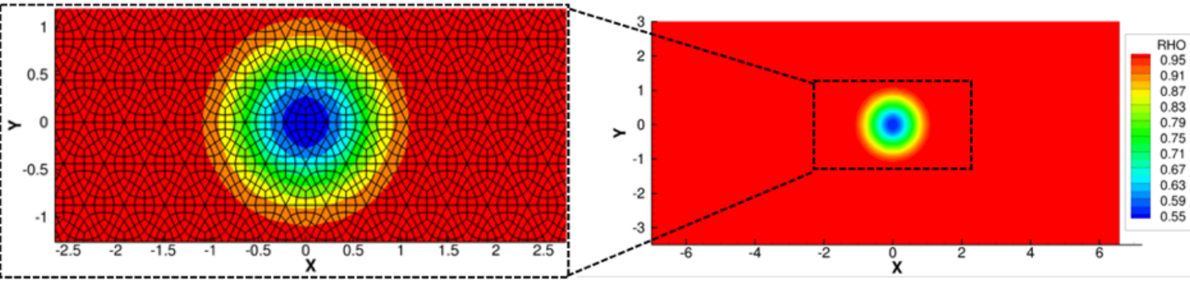


- M = 0.8, AoA 1.25, Inviscid transonic flow
- Formally currently only second-order accurate

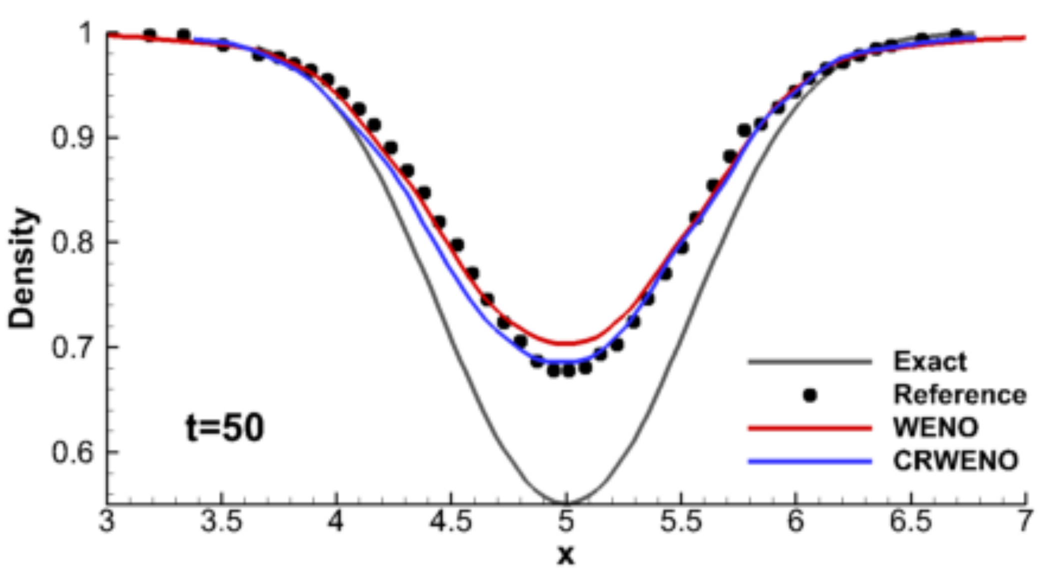
Isentropic Vortex

HAMSTR

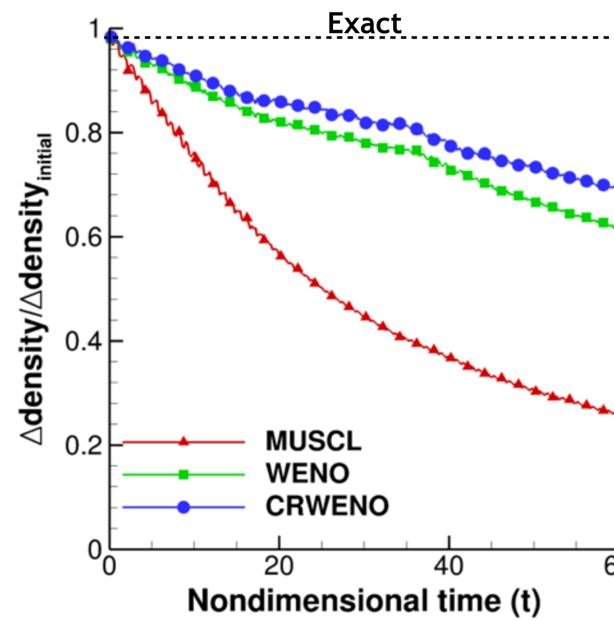
- 11,700 quadrilateral cells
- dt of 0.2 with 10 sub iterations
- Compare with DG (BDF2, *p* = 4)
- High-order type reconstruction can be beneficial



Grid and initial density contours



Density profile across vortex core

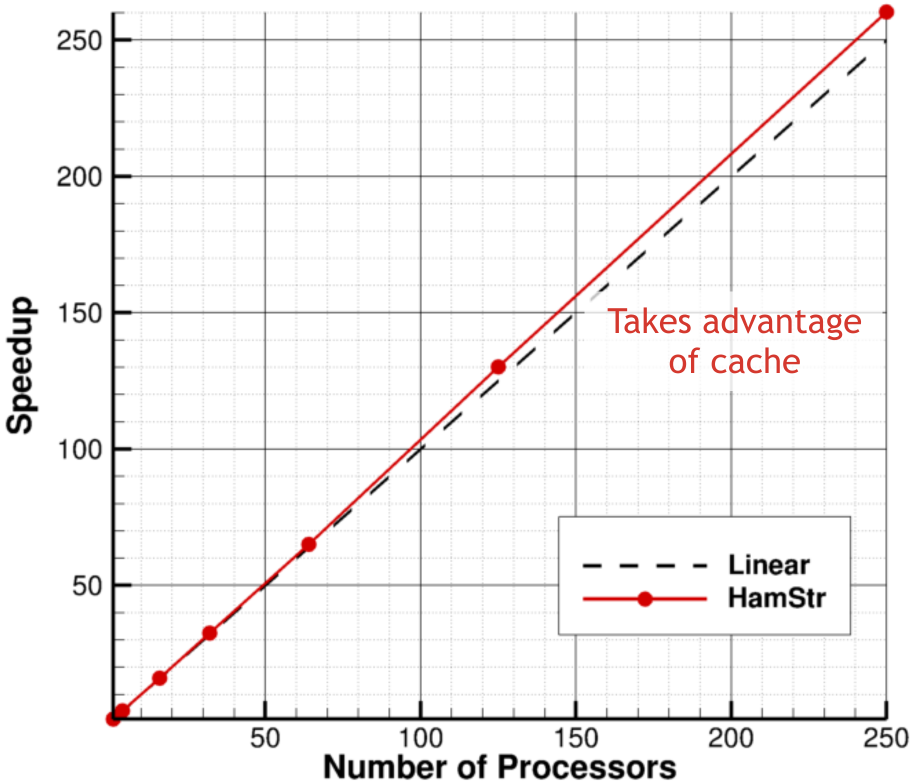


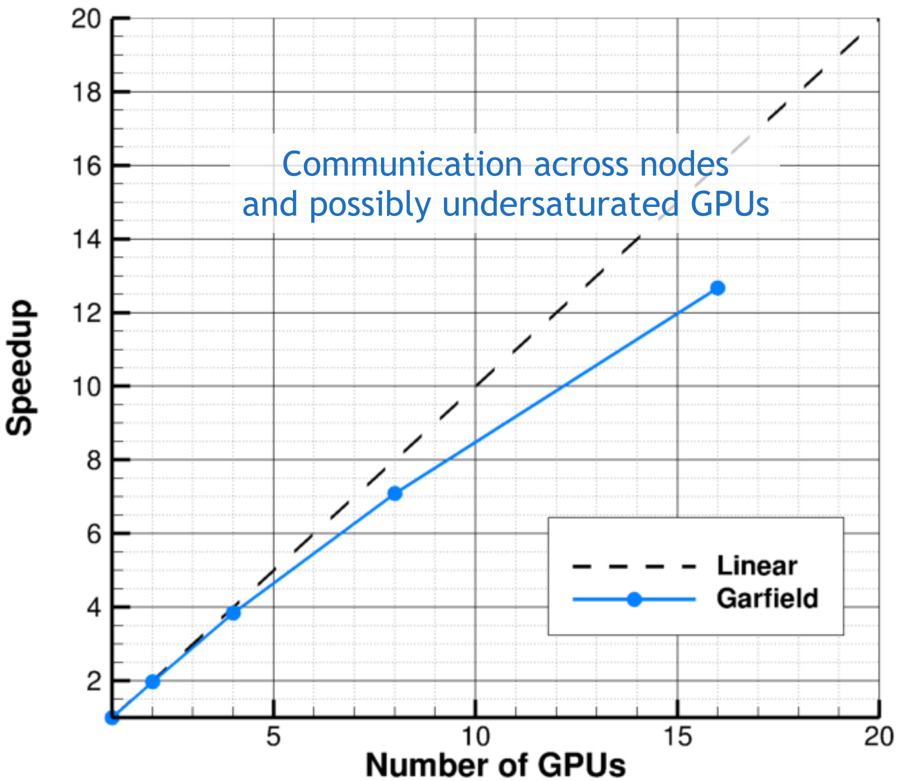
Reconstruction schemes

Wang, L., and Mavriplis, D. J., "Implicit Solution of the Unsteady Euler Equations for High-Order Accurate Discontinuous Galerkin Discretizations," Journal of Computational Physics, Vol. 225, No. 2, August, 2007

Scalability

HAMSTR-GARFIELD



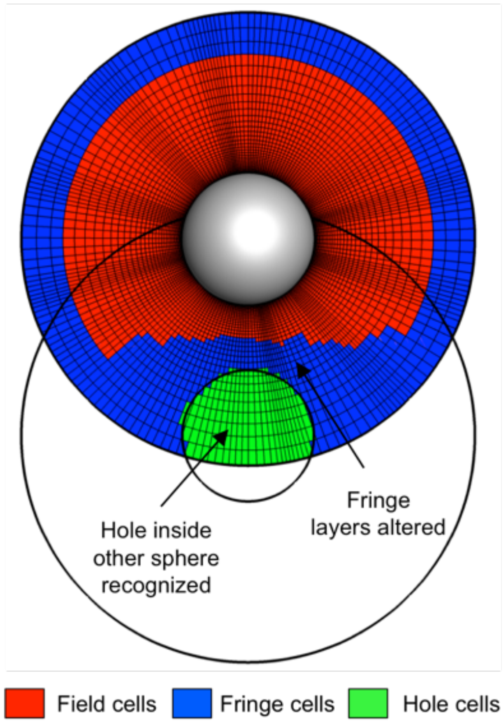


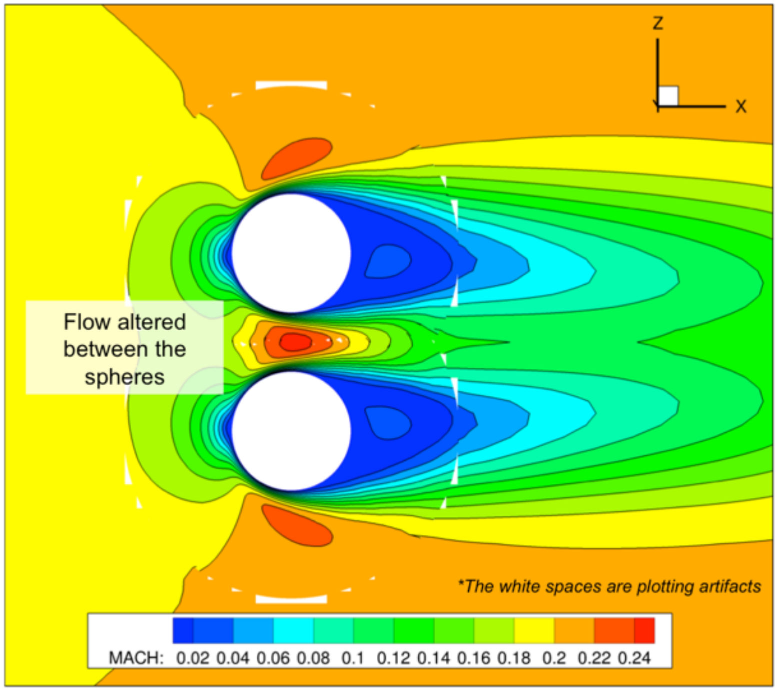
1 GPU on GARFIELD ~ 18 cores on OVERFLOW

Reasonable performance on multiple cores using both solvers (using MPI)

Overset Dual Spheres

HAMSTR





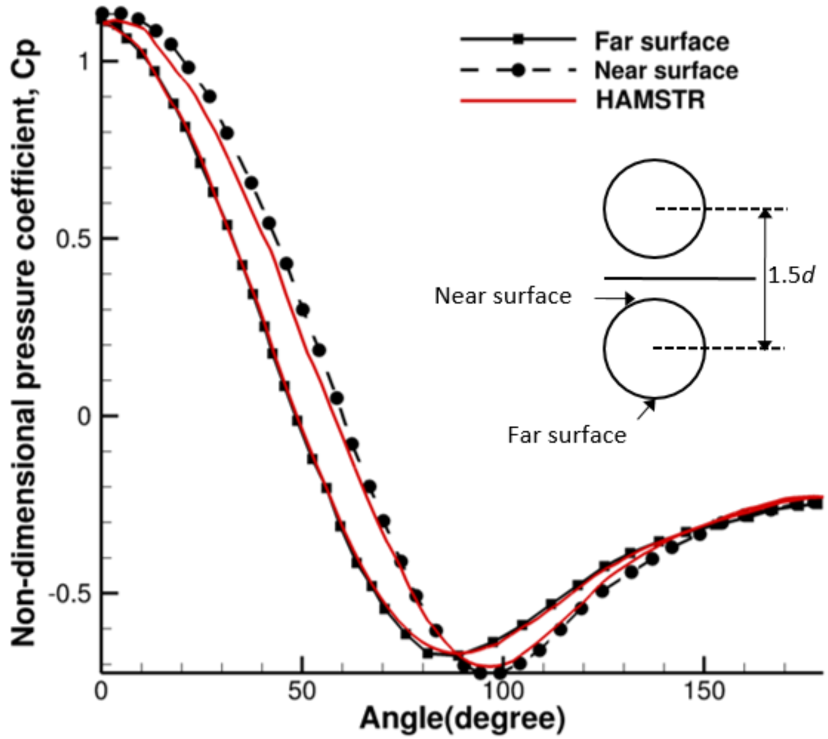
i-blanking map of top sphere

Mach contour lines

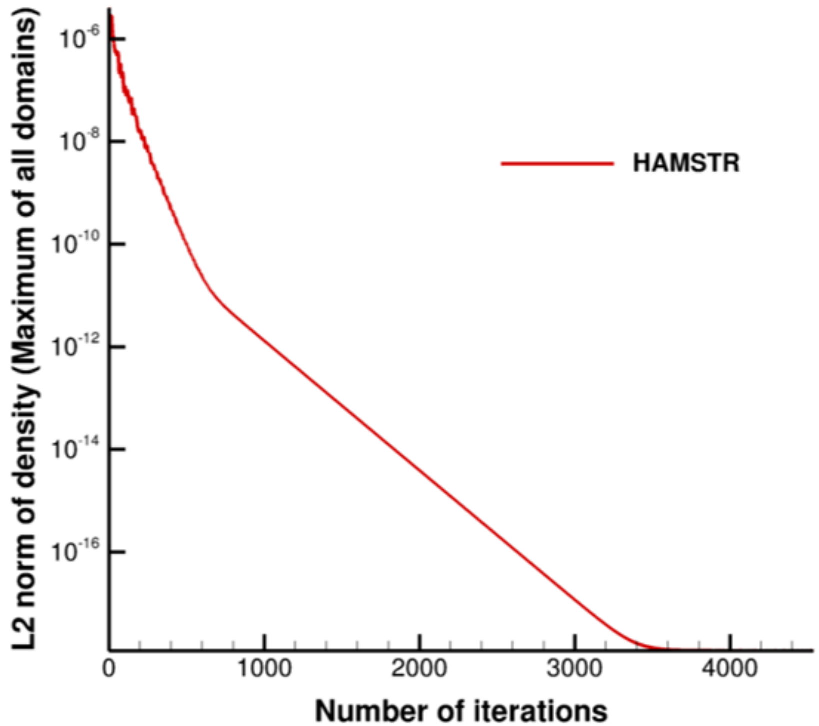
- **Separation distance between the two spheres is 1.5 diameter of the sphere**
- **Mach number 0.2, Reynolds number of 100 at 0^0 angle of attack**
- **15,360 surface quadrilaterals, 0.01*R* wall-spacing with 34 strands**
- **Velocity increment is observed by venturi effect between two spheres**

Overset Dual Spheres

HAMSTR



Surface pressure distribution



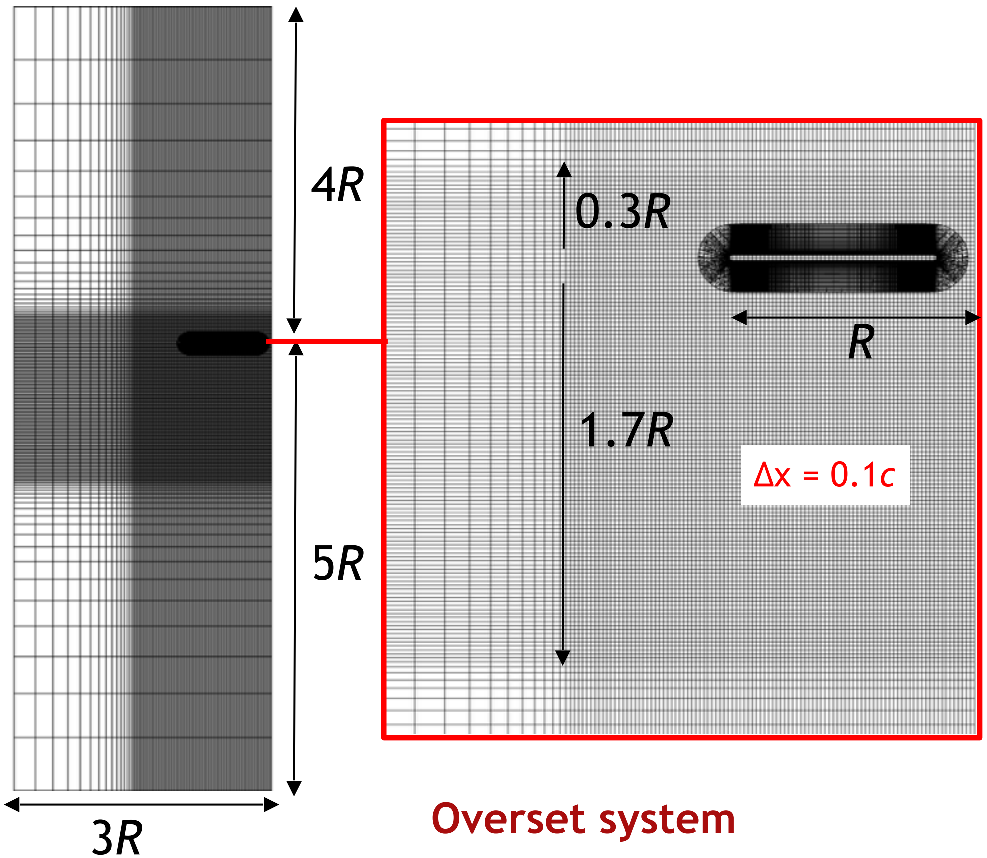
Residual convergence

- **Good agreement against reference results (numerical study)**
- **The solution converges to machine precision around 3,500 iterations.**

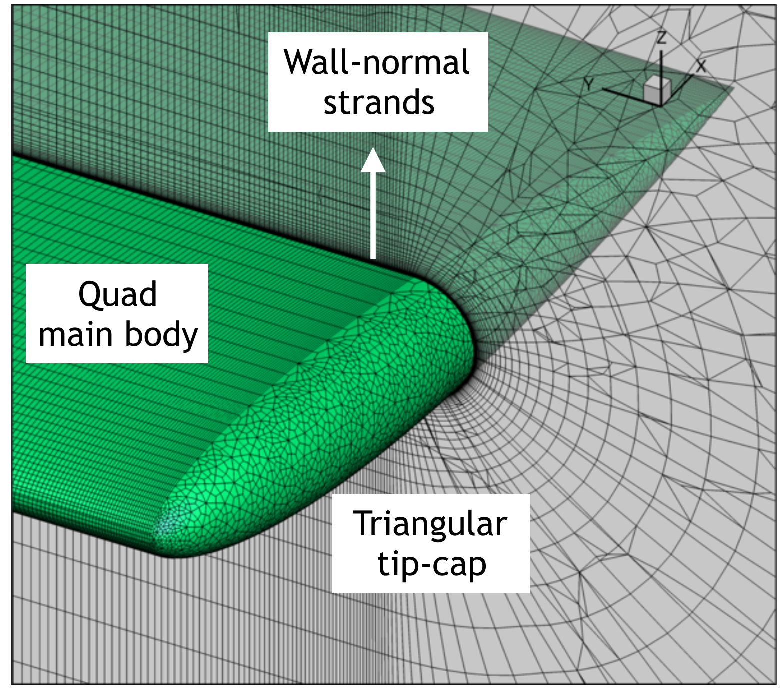
Kim, I., Elghobashi, S., and Siriganano, W. A., "Three-Dimensional Flow over Two Spheres Placed Side by Side," Journal of Fluid Mechanics, Vol. 246, (1), 1993, pp. 465-488.

Hovering Rotor

HAMSTR



Overset system



Near-body strand mesh

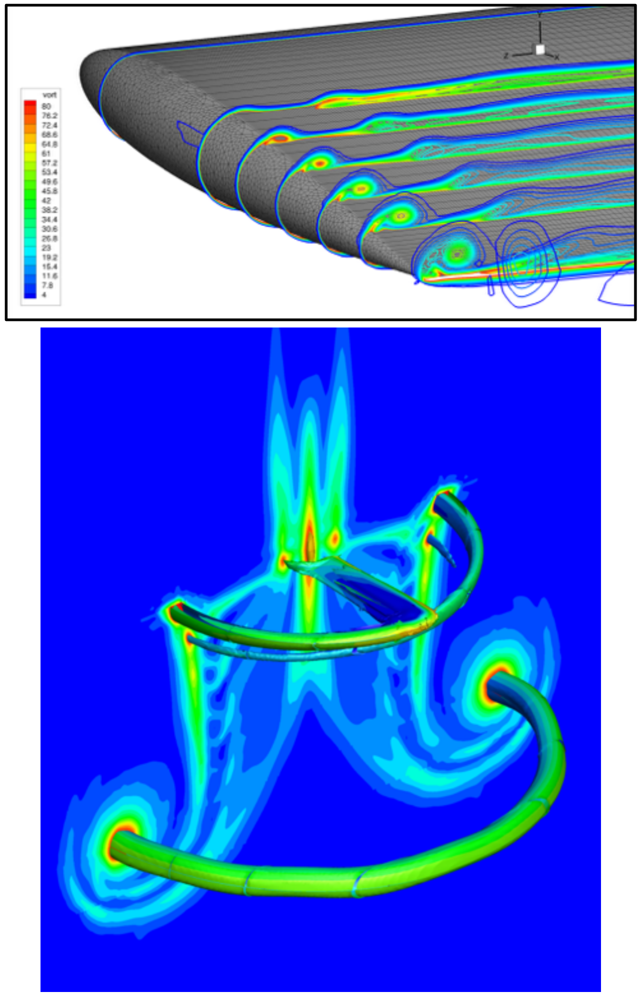
- **Untwisted, NACA 0012 blade of aspect ratio 6 at 8^0 collective, M_{tip} 0.877**
- **Mixed element surface mesh: 54 strands, wall spacing 10^{-5}, stretching 1.2**

Hovering Rotor

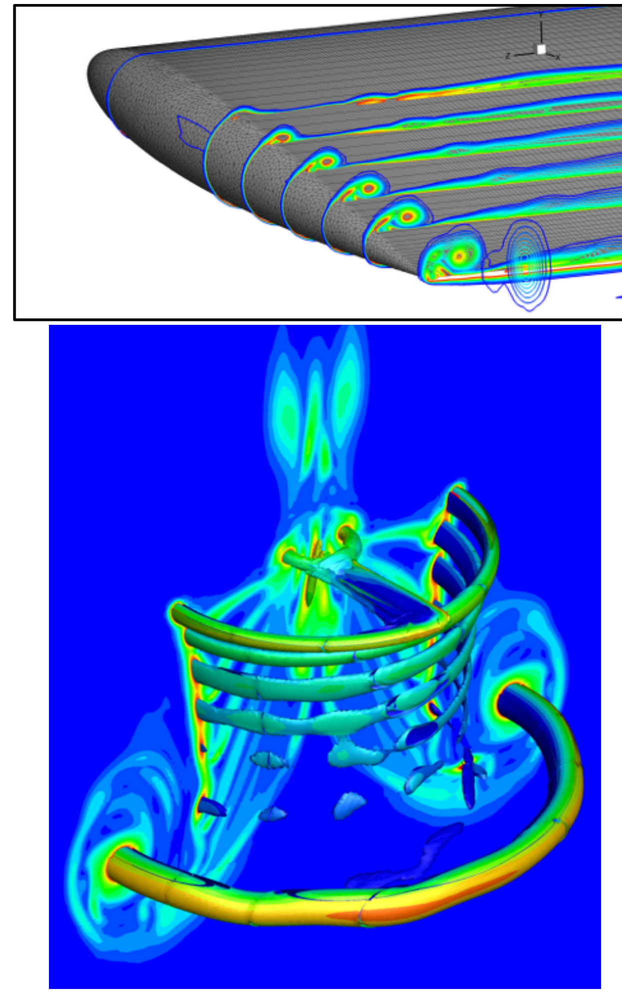
HAMSTR

Collective: 8^0
Mach tip: 0.877
Re tip: 3.93×10^6
timestep 1^0
Sub iterations 10

5th order reconstruction better preserves the vortical structure for longer wake-ages



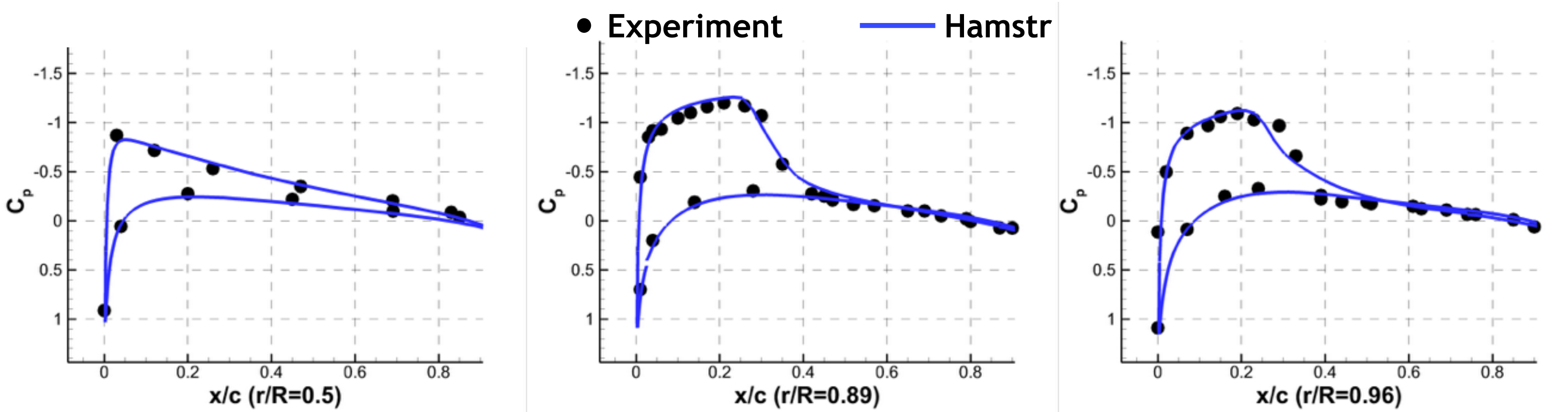
3rd order MUSCL reconstruction

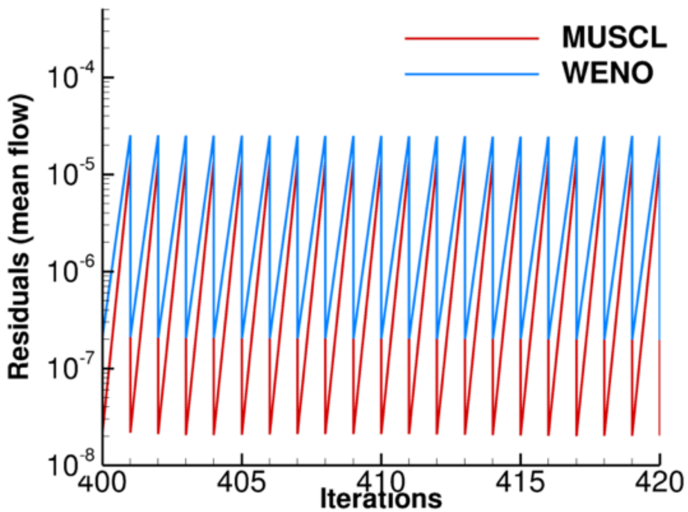


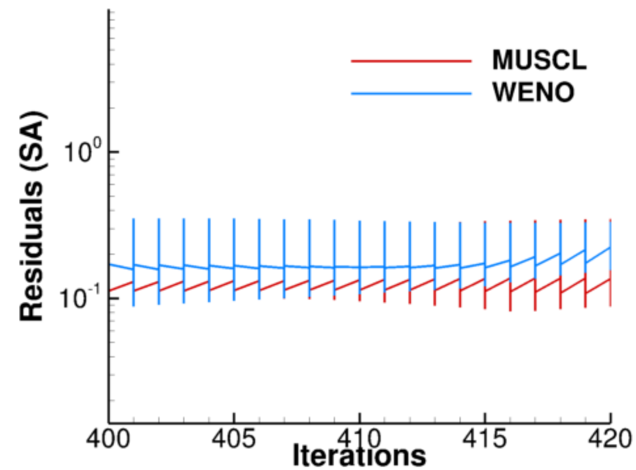
5th order WENO reconstruction

Hovering Rotor

HAMSTR



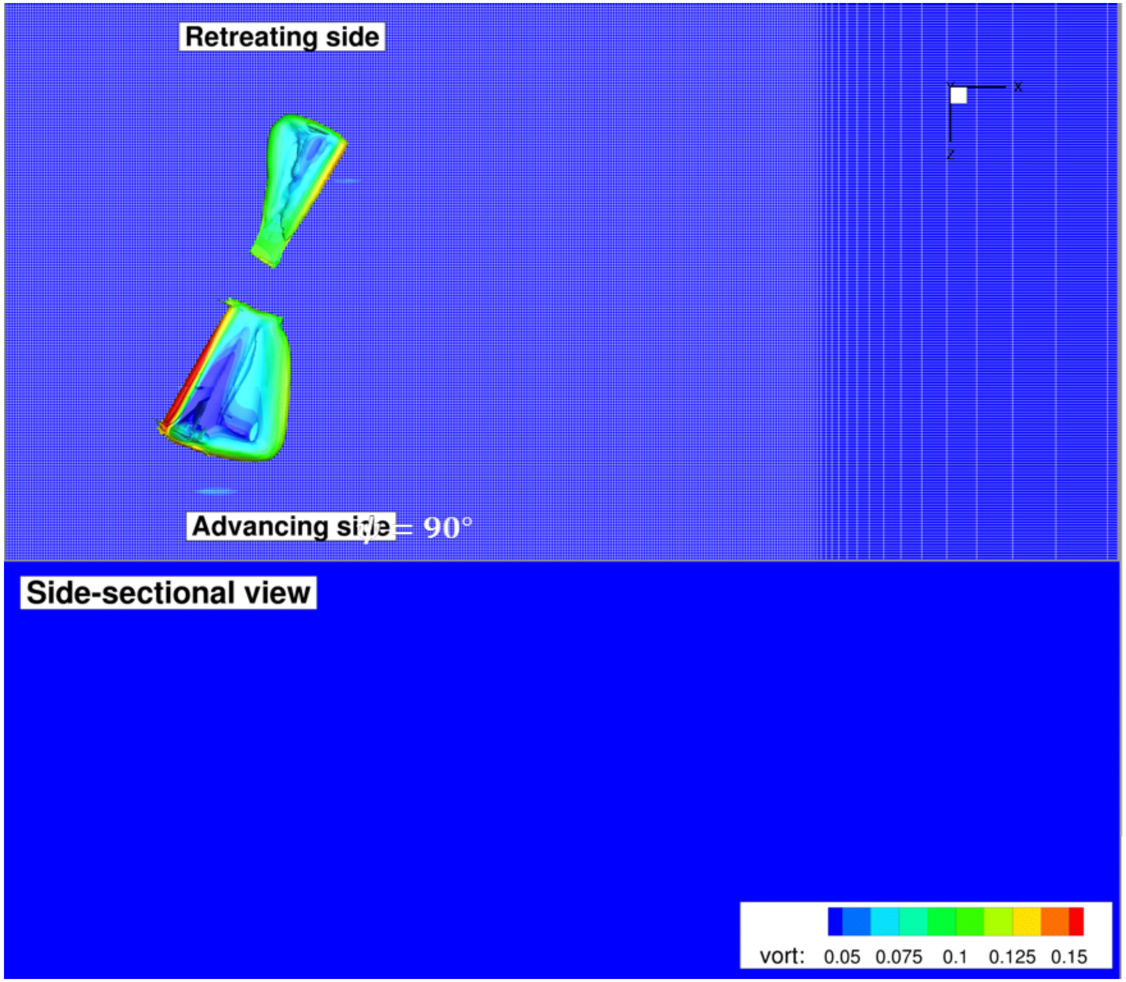


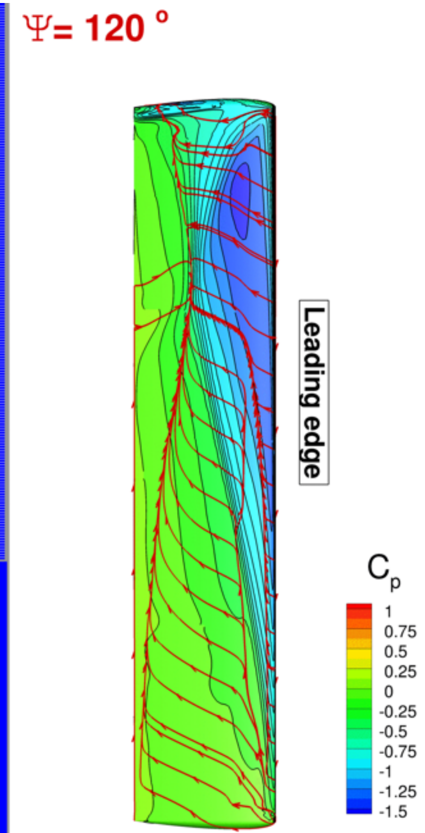


Good correlation with experimental pressure and good sub-iterative convergence

Forward Flight Rotor

HAMSTR

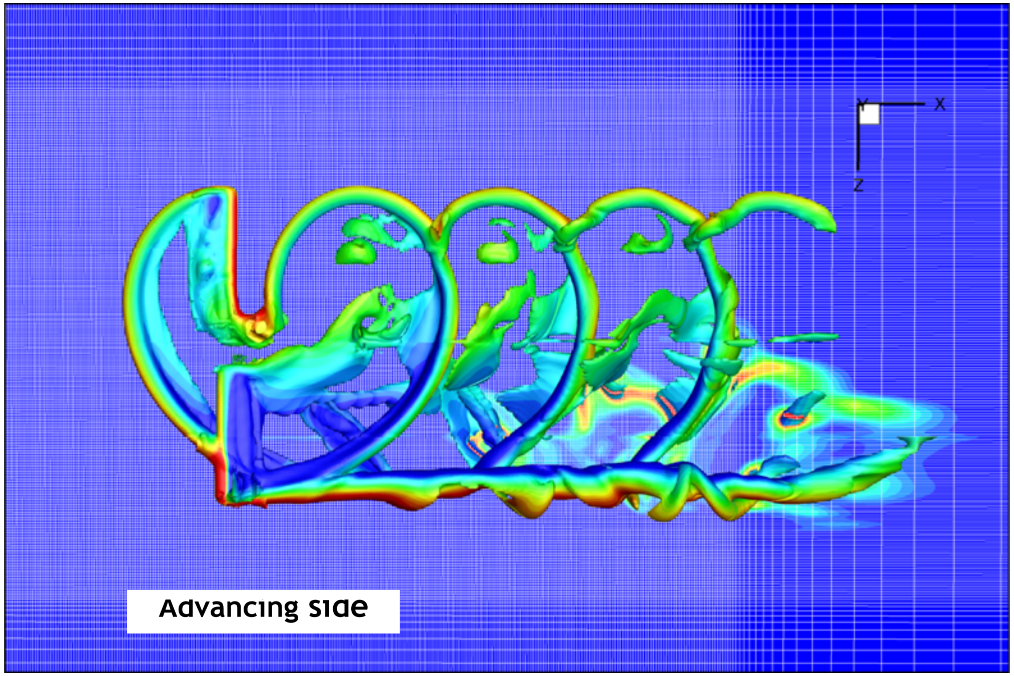




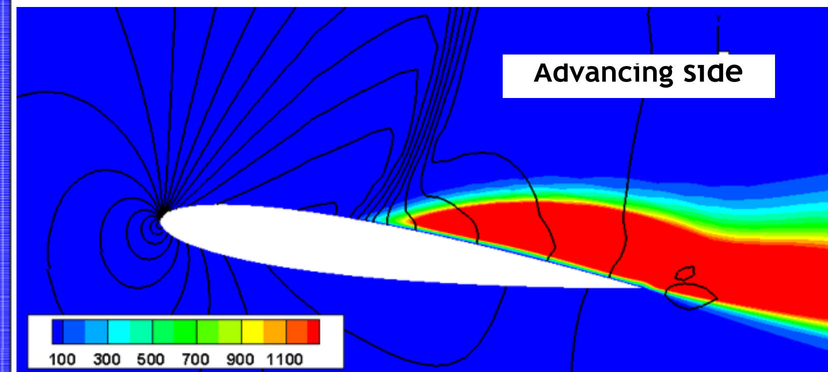
M_{tip} = 0.7 Collective = 8°, M_{inf}=0.2 (μ=0.28), Re = 3.93 million

Forward Flight Rotor

HAMSTR

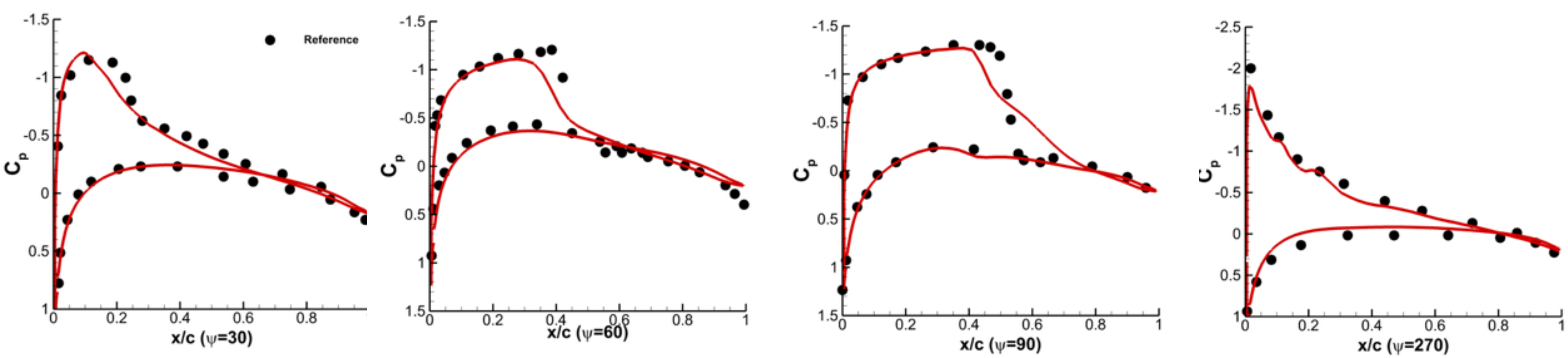


Iso-Vorticity contour



Shock induced vorticity
(Flood: Eddy viscosity, Line: pressure)

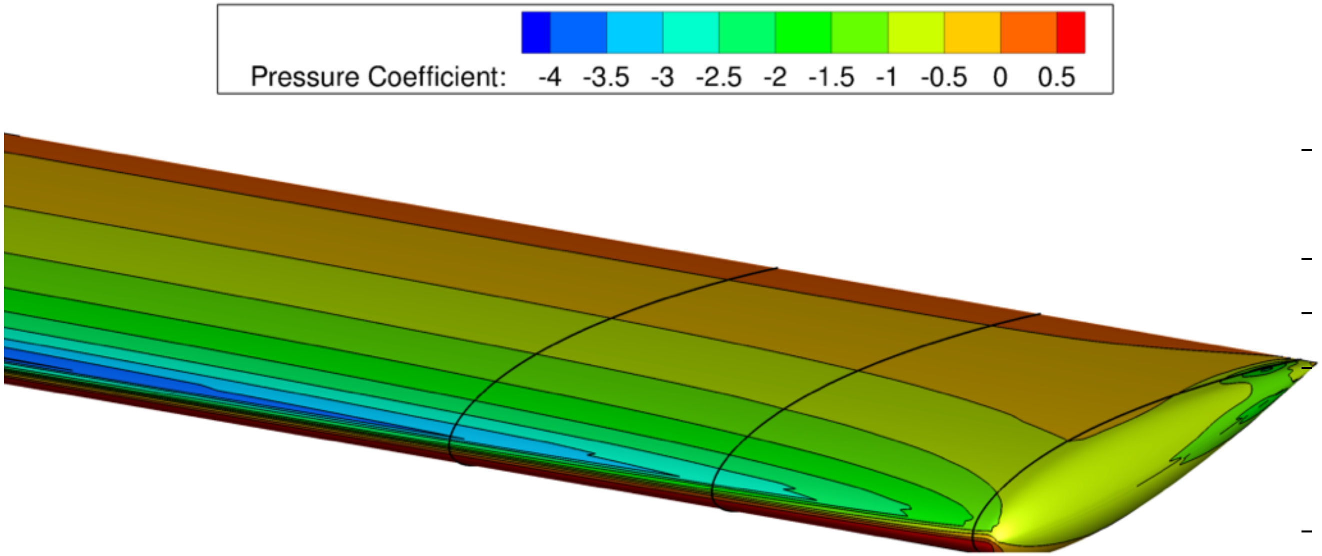
- Inviscid (Ref.)
- Hamstr



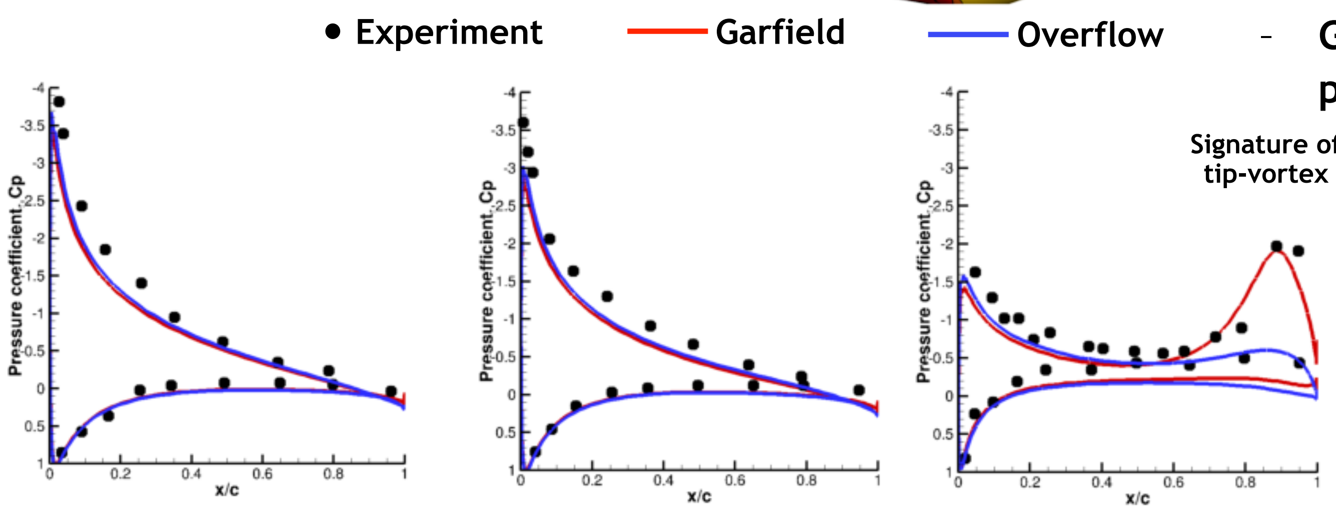
Sectional surface pressure at 90% of rotor radius

Turbulent Flow over Stub-Wing

GARFIELD



- NACA 0015 stub-wing with rounded tip cap
- 12^0 angle of attack
- 2.6×10^6 points
- Reasonable pressure distribution compared to experiments
- Tip-vortex well resolved
- Good agreement in pressure with overflow

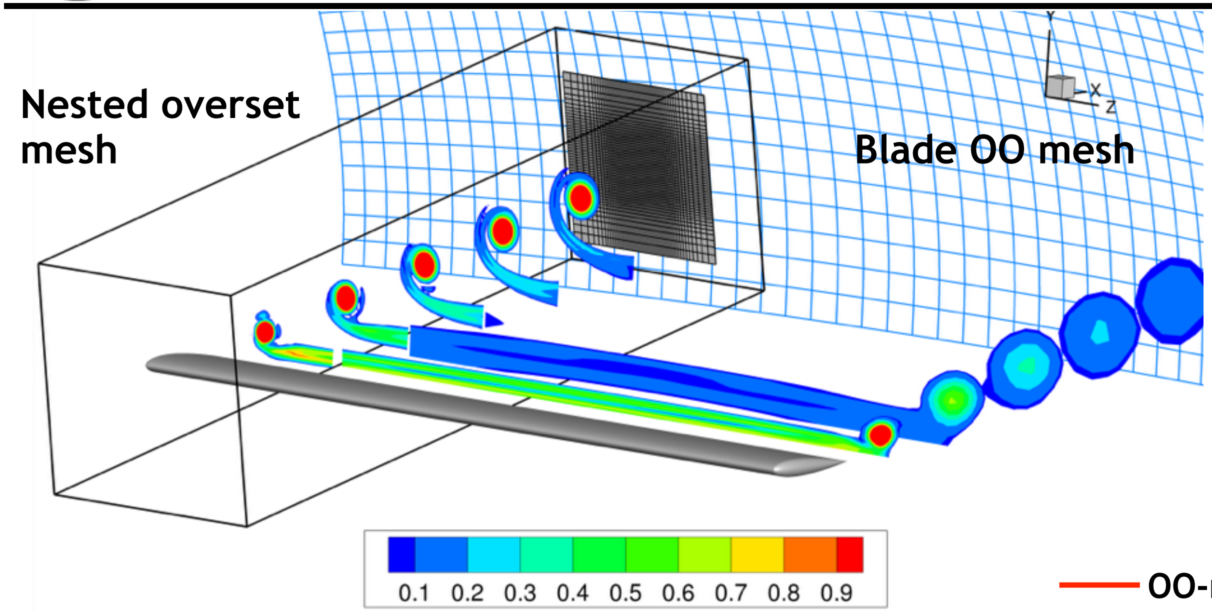


z/span = 0.676 z/span = 0.824 z/span = 0.971

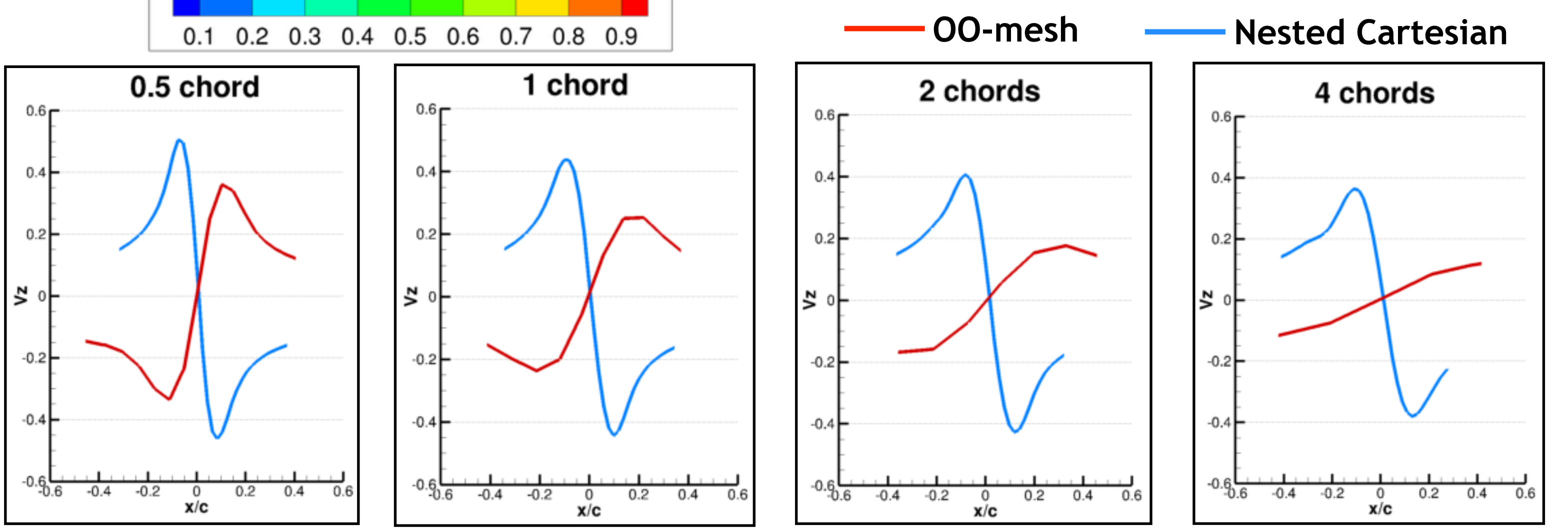
Overflow had a much coarser mesh at the tip!

Turbulent Flow over Stub-Wing

GARFIELD



- Nested Mesh: 0.83×10^6 nodes
- Minimum spacing: 0.02*c*
- Better vortex resolution with the nested mesh



Swirl velocity profiles at various downstream locations

Laminar Sphere

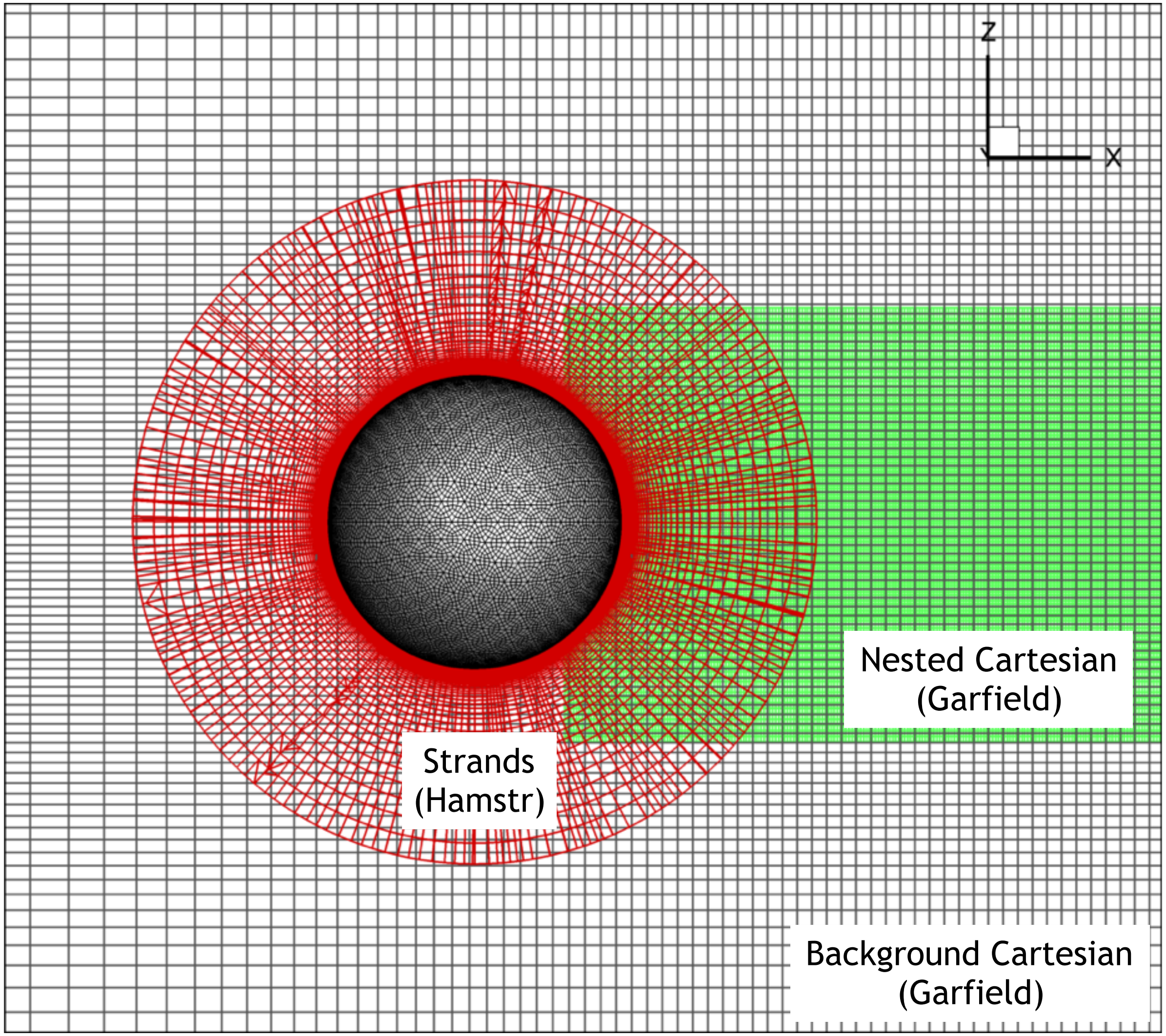
HAMSTR-GARFIELD

Hamstr

- Unstructured sphere
- 0.91×10^6 cells in volume
- 60 strand layers
- Wall spacing: 1×10^{-5}
- Stretching: 1.12
- 25 CPUs

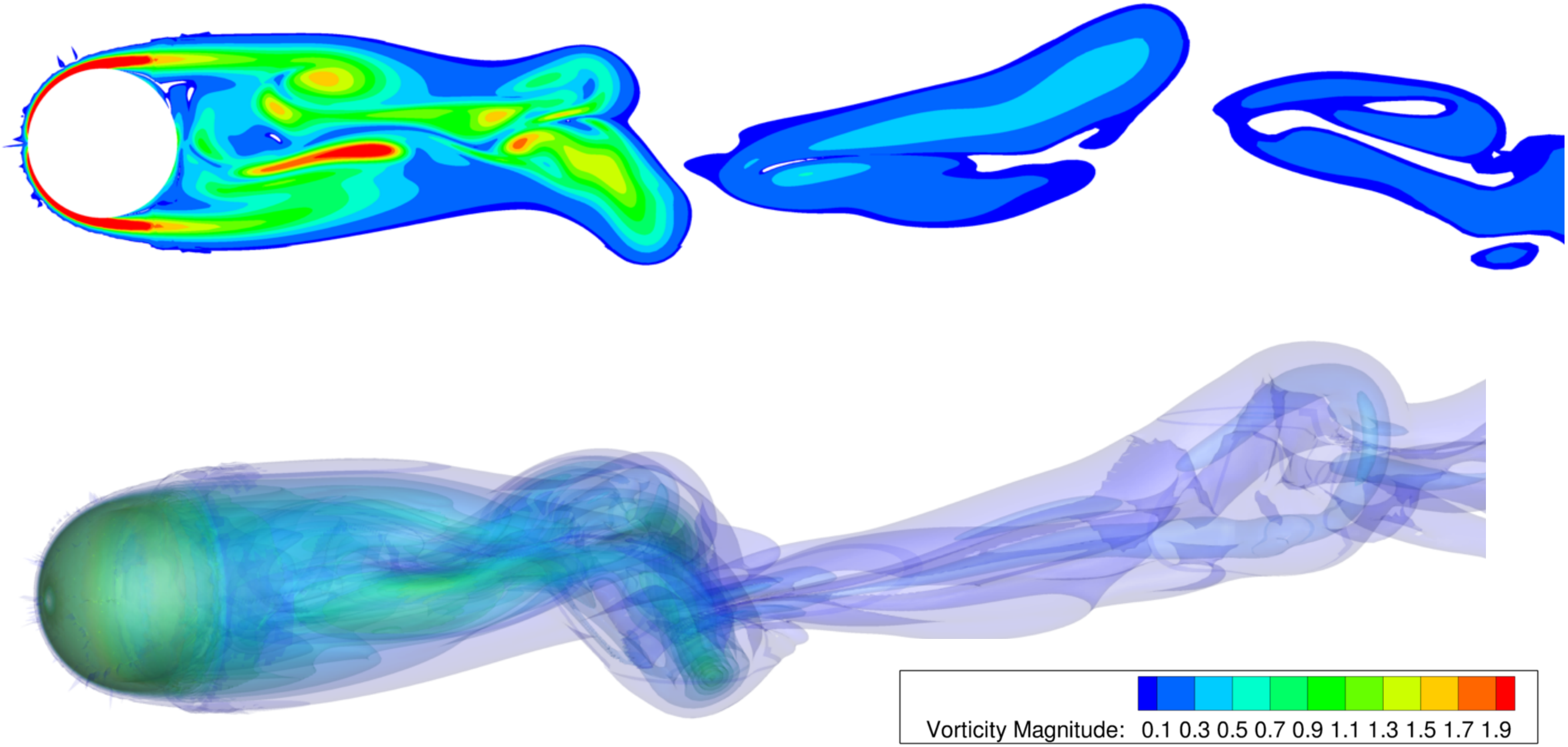
Garfield

- Nested: 5.8×10^6 cells ($0.02R$)
- Background: 3.3×10^6 cells ($0.1R$)
- 2 GPUs (Tesla K20, GTX Titan)



Laminar Sphere

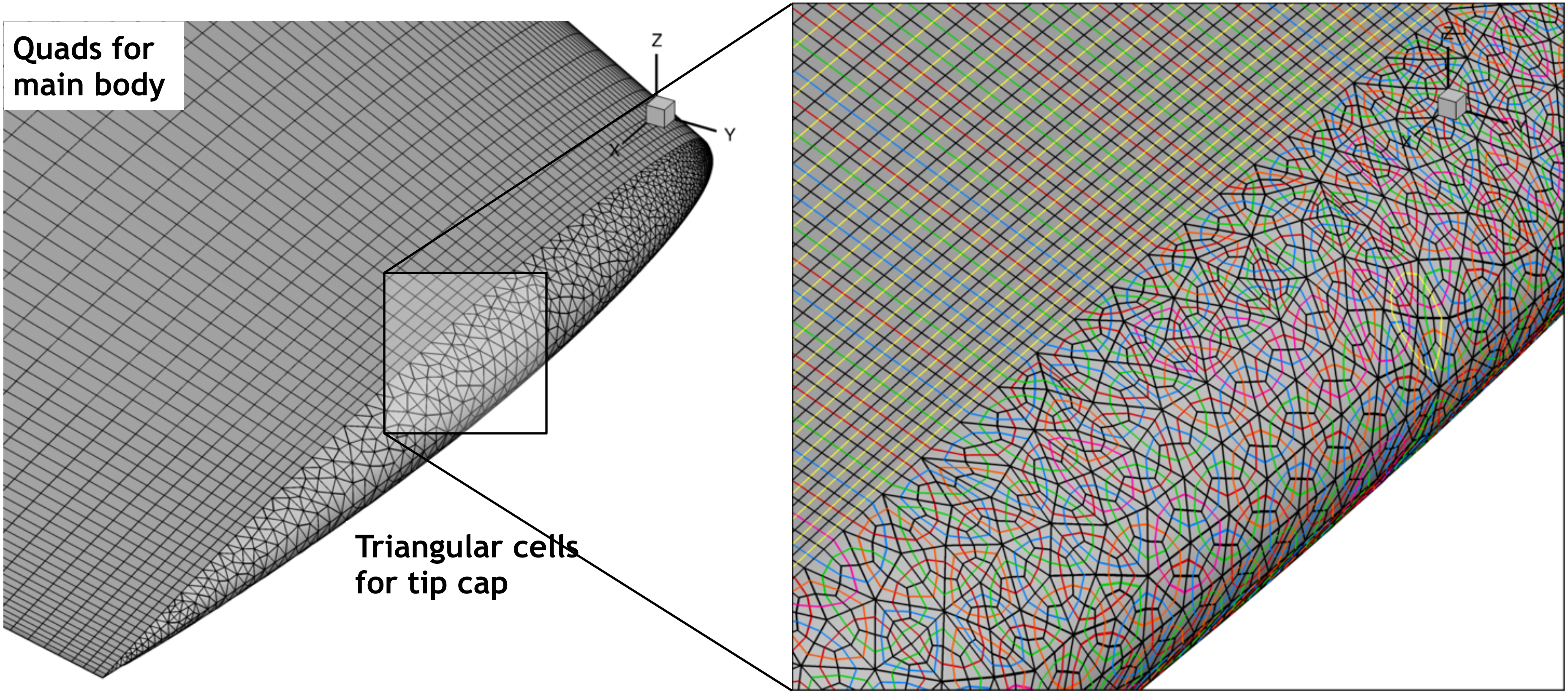
HAMSTR-GARFIELD



- **Laminar flow at Re=800**
- **With nested overset mesh, vortices are better captured and preserved**

Onera M6 Mesh

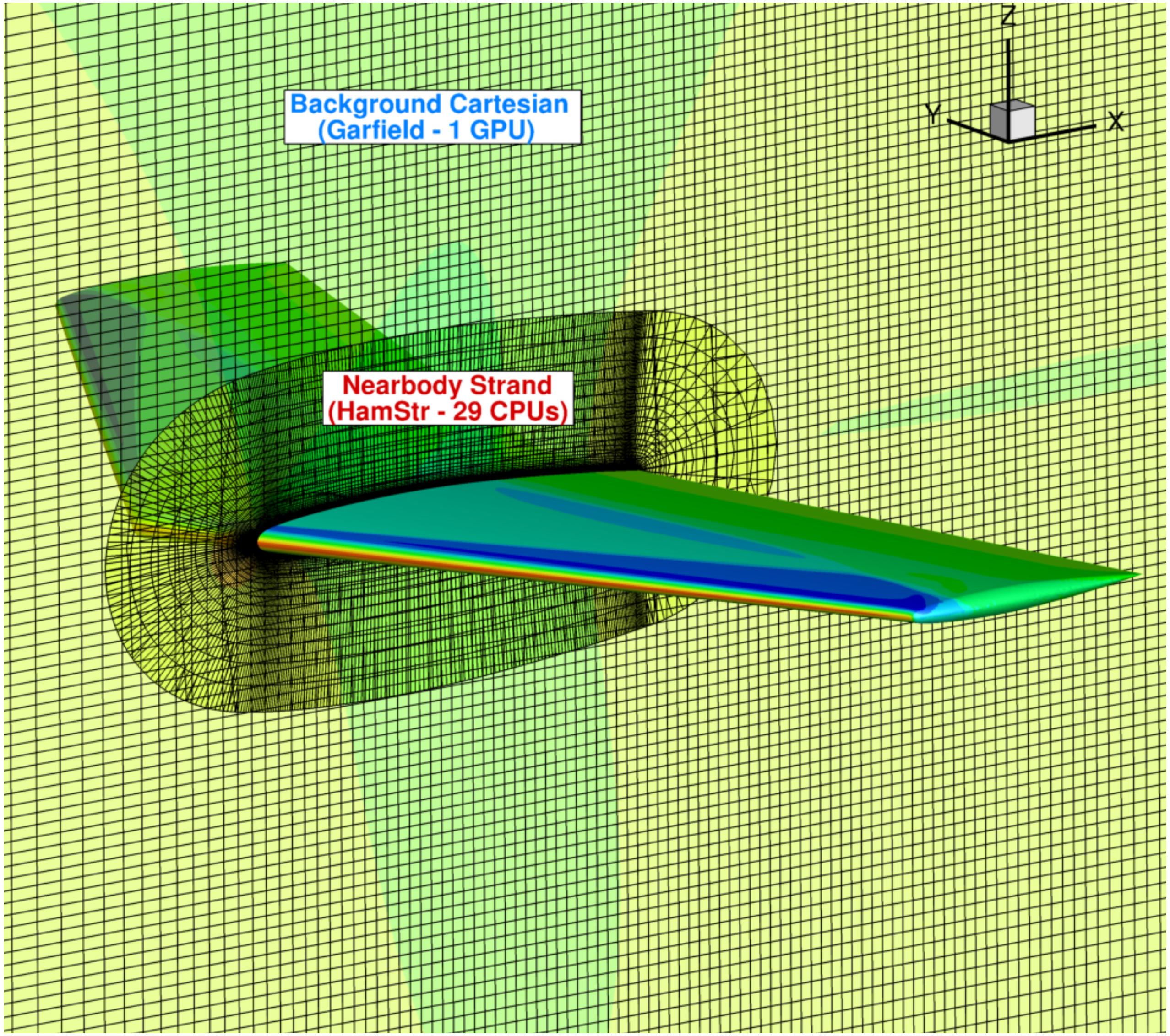
HAMSTR-GARFIELD



Hamiltonian loops pass through all the cells on the surface mesh

Onera M6 Mesh

HAMSTR-GARFIELD



Hamstr

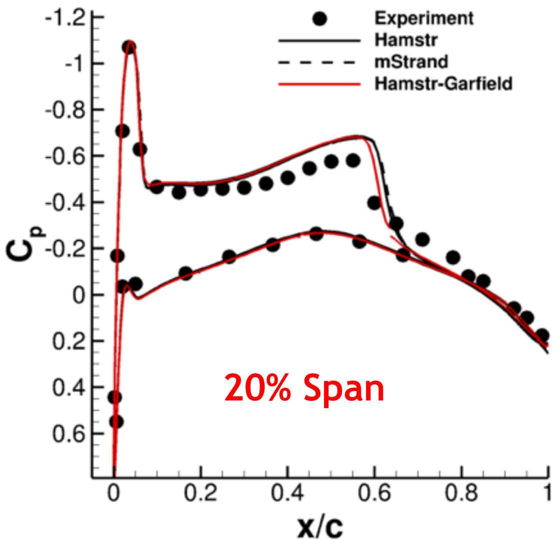
- 3.39×10^6 cells in volume
- 48 strand layers
- Wall spacing: 1×10^{-5}
- 29 CPUs

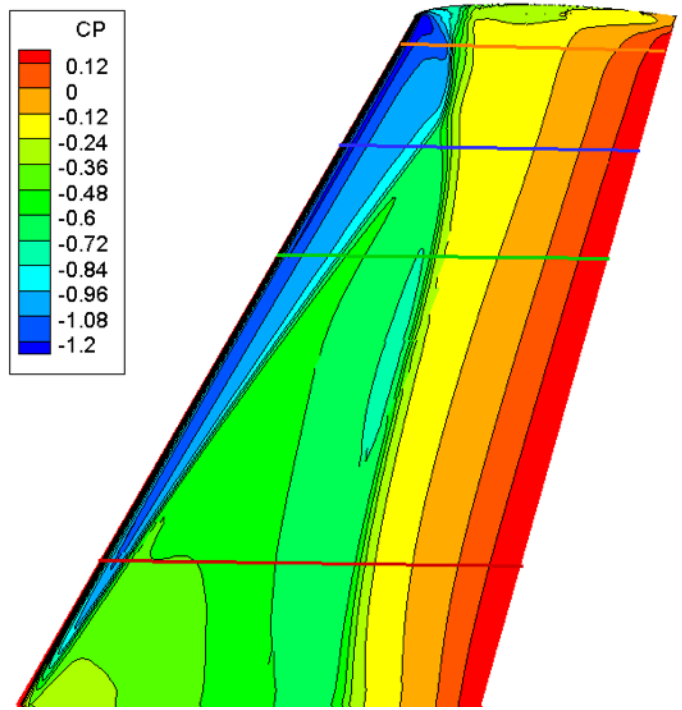
Garfield

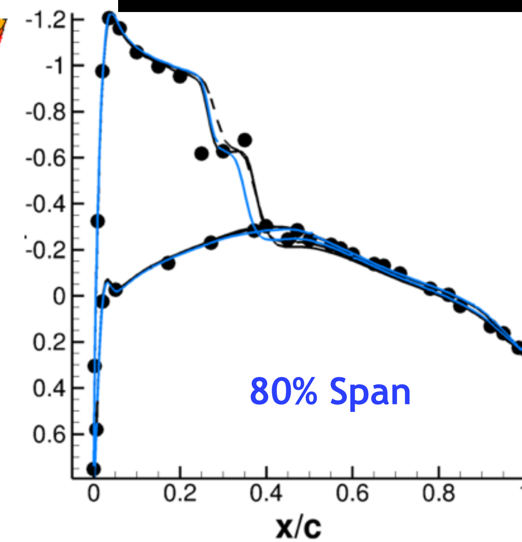
- 4.2×10^6 cells in volume
- Background Cartesian
- 1 GPU (Tesla K20)

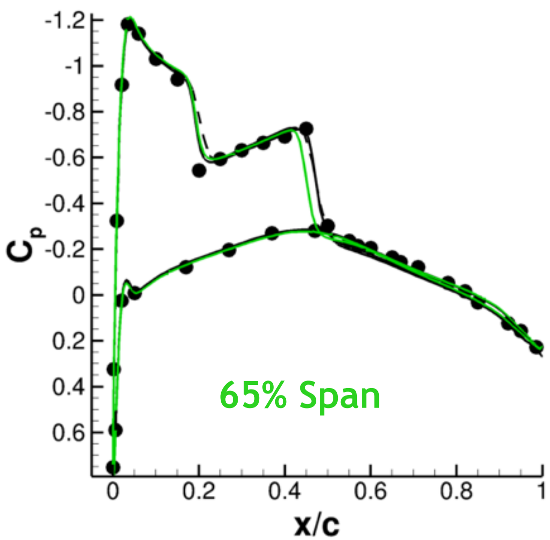
Onera M6 Solution

HAMSTR-GARFIELD

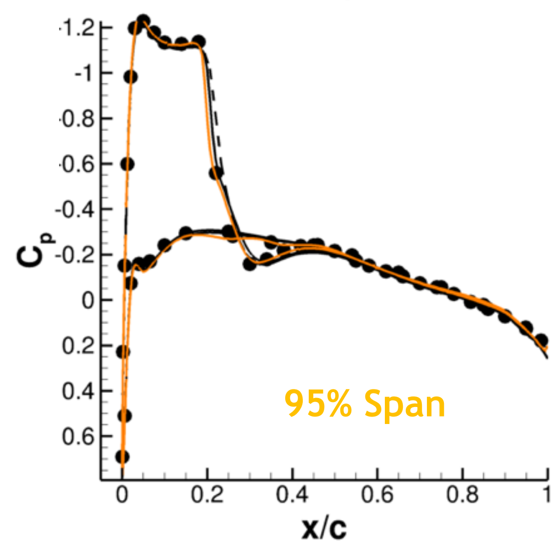






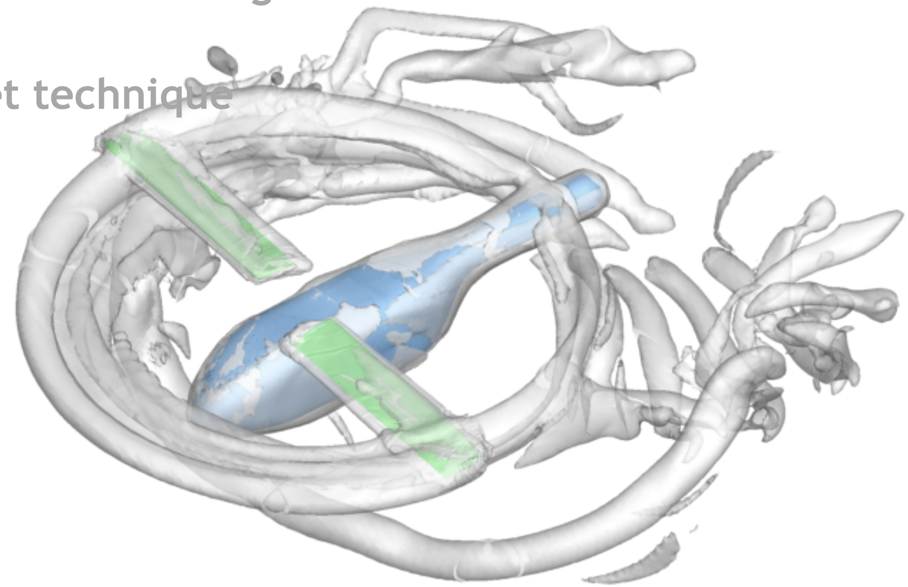


M = 0.8395
AoA = 3.06°
Re = 11.72 million



Outline

- Motivation and Introduction
- Methodology
  - HAMSTR: Line methods on unstructured grids
  - GARFIELD: GPU Accelerated solver on structured grids
  - TIOGA: Topology independent overset technique
  - Flow solvers
- Results
- Conclusions



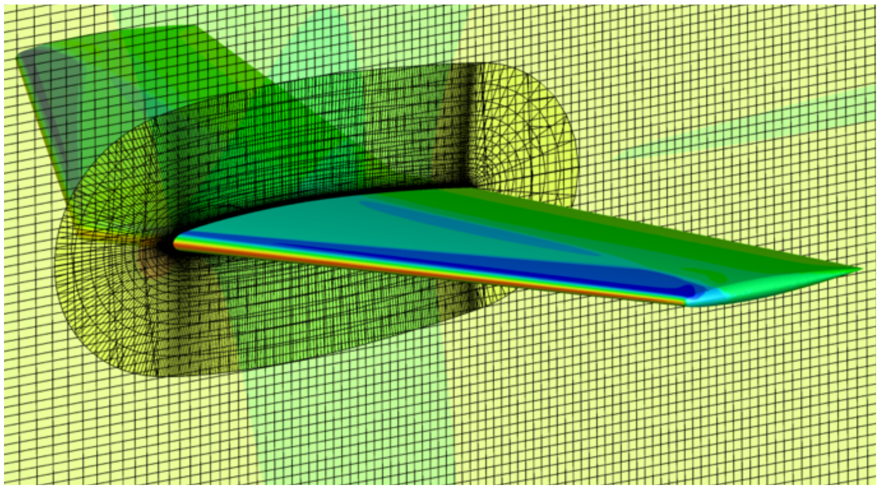
Conclusions

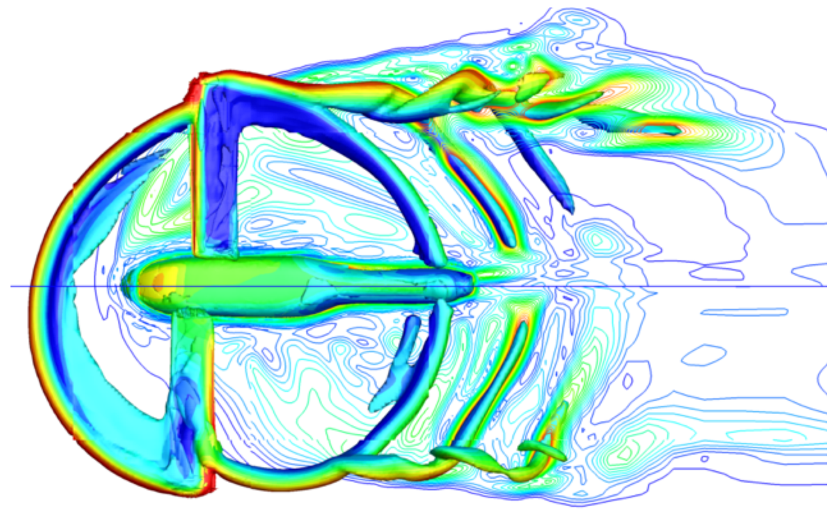
- Line-based solvers used for both structured and unstructured meshes
  - Hamiltonian paths and strand grids used for unstructured grids
  - Conventional lines used for curvilinear grids
  - Enables the use of high-order type reconstruction schemes (e.g., MUSCL, WENO) and line-based inversion techniques
- Hardware acceleration through Graphics Processing Units
  - RANS equations solved entirely on multiple GPUs using MPI
  - Reasonable scalability with some penalty for information exchange across nodes
- Python based framework developed for practical aerodynamic flows
  - Allows for the most optimum solver to be used for a given grid topology
  - Demonstrated capability of the solvers over a wide range of cases

Acknowledgements

- Air Vehicle element of the HPCMP CREATE program, particularly to Robert Meakin, Nathan Hariharan, and Roger Strawn
- Jay Sitaraman for his help in integrating TIOGA and technical expertise
- UMDs Deepthought II high-performance computing facility

A Structured-Unstructured Overset Framework for Aerodynamic Flows using CPU/GPU Computing





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